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FULL RESEARCH PAPER
Cardiovascular disease

Incidence and burden of cardiovascular disease attributable to extreme heat in China

Xuyan Pei [1], Haosu Tang [2], Congyi Zheng [1], Yue Zhang [3], Muyi Sun [4], Qinglan Jia [1], Siyu Liu [5], Xin Wang [1], Ye Tian [1], Xue Cao [1], Yixin Tian [1], Xue Yu [1], Nuerguli Tuerdi [1], Chenye Chang [1], Yujie Zhang [1], Fan Li [1], Jialu Yang [1], and Zengwu Wang [1]*; on behalf of the CVD surveillance in China (CDSC) Working Group

[1]Division of Prevention and Community Health, National Center for Cardiovascular Disease, National Clinical Research Center of Cardiovascular Disease, State Key Laboratory of Cardiovascular Disease, Fuwai Hospital, Peking Union Medical College & Chinese Academy of Medical Sciences, Beijing 102308, China; [2]Department of Geography, University of Sheffield, Sheffield S3 7ND, UK; [3]Department of Epidemiology, School of Public Health, Shanxi Medical University, Key Laboratory of Coal Environmental Pathogenicity and Prevention, Ministry Education, Taiyuan 030001, China; [4]School of Public Health, Bengbu Medical University, Bengbu 233030, China; and [5]Department of Epidemiology, School of Public Health, Medical College of Soochow University, Suzhou 201701, China

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Aims

The increasing frequency of heat events driven by climate change poses a serious challenge to cardiovascular health. This study aimed to investigate the relationship between high temperature and acute cardiovascular disease (CVD) incidence in China and to quantify the heat-related burden of CVD.

Methods and results

A total of 856 357 incident acute CVD cases were used from CVD surveillance in China in 2023. A distributed lag non-linear model was applied to evaluate the dose–response relationship between temperature and CVD incidence, as well as the best linear unbiased prediction of the minimum incidence temperature (MIT). The heat-related burden was quantified using attributable fraction and attributable number for two temperature ranges: all heat and extreme heat. Higher temperatures were associated with an increased risk of acute CVD incidence. Extreme heat exposure resulted in a cumulative relative risk (RR) of 1.17 [95% confidence interval (CI) 1.05–1.30], with the highest cumulative risk observed on the fourth day following exposure. All heat exposure accounted for 3.19% of CVD cases, while extreme heat contributed to 0.08%. The burden was particularly pronounced among individuals aged ≥65 years (RR = 1.20, 95% CI 1.05–1.37), rural populations (RR = 1.18, 95% CI 1.01–1.37), and those living in temperate monsoon and temperate continental climates (RR = 1.25, 95% CI 1.05–1.49). Minimum incidence temperature varied geographically, ranging from 16.0°C in northern regions to 26.2°C in southern regions, with the highest MITs concentrated in tropical areas.

Conclusion

These findings emphasize the urgent need for region-specific public health strategies that integrate climate change adaptation and CVD prevention to mitigate the growing health risks associated with rising temperatures.

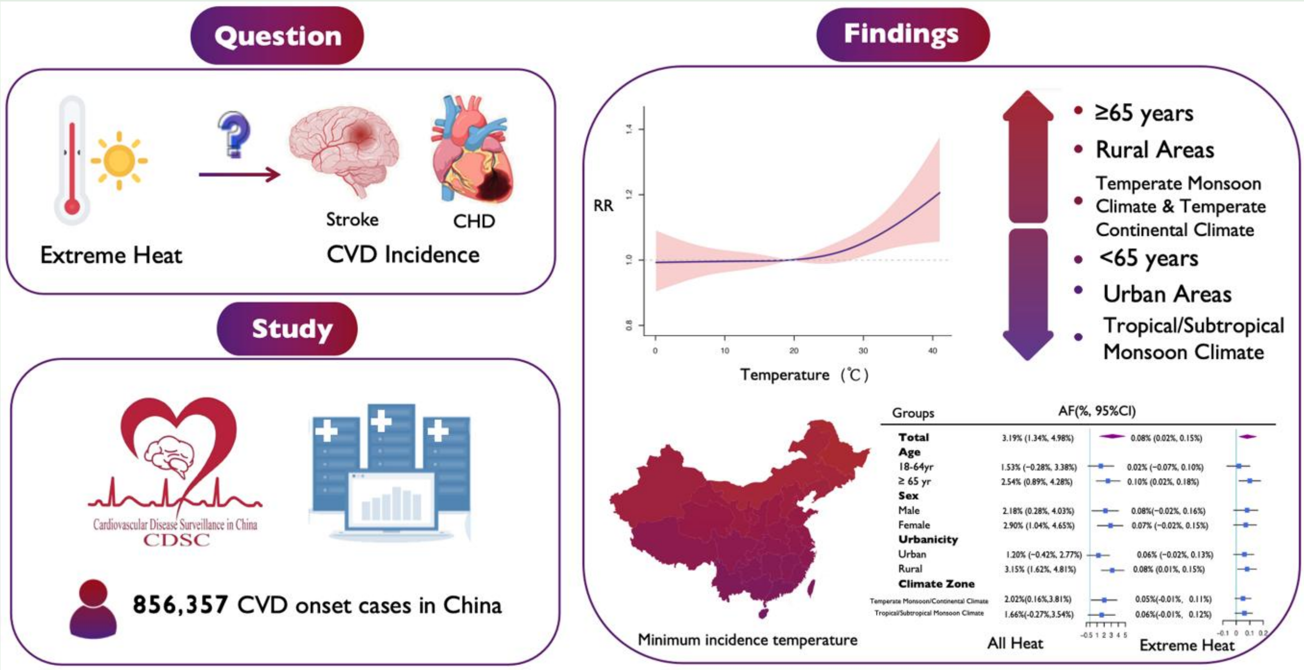
Lay summary

This study examined the relationship between high temperatures and acute cardiovascular disease (CVD) incidence in China and quantified the heat-related burden.

- Higher temperatures increased the risk of acute CVD, with extreme heat exposure leading to a 17% higher risk, peaking on the fourth day after exposure.
- The heat-related burden was more pronounced among older adults (≥65 years), rural populations, and residents of the northern region, highlighting the need for targeted public health strategies.

* Corresponding author. Tel: +8613601366932; Email: wangzengwu@foxmail.com

Graphical Abstract



Keywords Attributable fraction • Cardiovascular disease • Environmental exposure • Extreme heat • Incidence and burden

Introduction

Significant public health achievements in cardiovascular disease (CVD) prevention have been achieved in recent decades, largely attributed to interventions targeting traditional risk factors such as high blood pressure, elevated cholesterol, and smoking.[1–3] Despite this progress, the burden of CVD remains substantial, particularly with the increasing trends of urbanization and ageing populations. In 2022, CVD was responsible for an estimated 19.8 million deaths worldwide, resulting in 396 million years of life lost (YLLs) and an additional 44.9 million years lived with disability (YLDs).[4] Entering the era of precision medicine, further reductions of the CVD burden require expanding prevention strategies beyond conventional risk factors to incorporate non-traditional ones, such as environmental exposures, which can provide novel insights into CVD prevention. Due to increased greenhouse gas emissions from human activities, global warming has become increasingly severe. This leads to a significant rise in both the frequency and the intensity of extreme heat,[5] imposing a substantial burden on cardiovascular health.

High temperature can lead to physiological changes, including increased heart rate, heightened blood viscosity, and dehydration due to excessive sweating, which collectively place additional strain on the heart and increase the risk of CVD.[6] Numerous studies have documented heat-related CVD mortality, consistently showing trends that align with established physiological mechanisms[7–10]. With the shift in CVD prevention strategies towards early health interventions, it becomes even more critical to explore the relationship between high temperature and CVD incidence, and the burden on the healthcare system should also be measured in terms of incidence. However, relatively few studies have investigated the relationship between high temperature and the risk of incident CVD,[11–13] and even fewer have quantified heat-related incidence burden in terms of attributable fraction (AF) or attributable number (AN),[14] particularly across multiple counties in China. Furthermore, the effect of ambient temperature on CVD hospitalizations varies by population characteristics.[12] This highlights the importance of better understanding heat-related risks in the context of CVD and underscores the need for targeted, population-specific prevention strategies.

To address these gaps, we use the most up-to-date and comprehensive registration data to investigate the relationship between heat exposure and acute CVD incidence in China. Moreover, we calculate the AF and AN, which serve as burden measures that extend beyond relative risk (RR) by estimating the actual impact of heat exposure on population health. These measures are critical for informing targeted interventions and policies to ultimately strengthen resilience against the health impacts of climate change.

Methods

Data sources

This study was based on the CVD surveillance in China, a nationwide surveillance launched in 2021. This system covered ∼238 million people, accounting for 16.9% of the population of China, and aimed to assess the incidence of acute CVD among Chinese residents aged 18 years and older. All medical institutions within the surveillance network are required to report CVD cases using a standardized case report form. In-hospital CVD cases—including those from inpatient, emergency, and outpatient/clinic settings—are recorded by the responsible clinicians or trained staff at each institution. For fatal out-of-hospital CVD events and cross-regional medical incidents, certified physicians from primary healthcare institutions conduct on-site investigations during routine public health activities to complete case reports. Additionally, annual mortality registration data are crossreferenced with the surveillance database, with subsequent verification and supplementary data collection conducted also by primary care physicians. More detailed information can be found in the Supplementary material.

Major cardiovascular outcomes were monitored, classified using the International Classification of Diseases, 10th Revision (ICD-10), coding system, ensuring precise and standardized categorization. Stroke encompassed a spectrum of conditions, ranging from subarachnoid haemorrhage to ischaemic stroke, broadly classified under Codes I60, I61, I63, and I64, while explicitly excluding Code I62. Coronary heart diseases (CHDs) with accurate and reliable diagnoses were selected, including acute myocardial infarction, angina pectoris, and sudden cardiac death. Acute myocardial infarction was classified as Codes I21–I22, and angina pectoris was represented by Code I20, specifically highlighting cases treated with percutaneous transluminal coronary angioplasty (PTCA), stent implantation, and/or coronary artery bypass grafting (CABG). Sudden cardiac death was categorized under Code I46.1. Cases with chronic or recovering CVD were explicitly excluded.

All districts were defined as urban areas, and all counties, including county-level cities and banners, were defined as rural areas. The classification was based on the participant's habitual residence, defined as having lived in the location for 6 months or more.

To ensure data reliability, the quality of each monitoring site was rigorously evaluated through assessments of validity, completeness, uniqueness, and comparability. Data for cases diagnosed between 1 January 2023 and 31 December 2023 were extracted from the database. After data quality control, a total of 856 357 CVD onset cases were included in this study.

Environmental exposure

We acquired daily meteorological observations in 2023, including maximum, minimum, and mean temperatures, along with relative humidity, from over 2400 meteorological stations via the China Meteorological Data Sharing Service System (see Supplementary material online, *Figure S1*). Bilinear interpolation was applied to estimate specific daily environmental exposures for each participant. We also evaluated the results using other interpolation methods, including bicubic and inverse distance weighting. The Pearson correlation coefficients between these results and those obtained using bilinear interpolation were all close to 1 and statistically significant at the 99% confidence level. The extreme heat was defined as the 95th percentile of daily maximum temperatures. In addition, daily air pollution data for particulate matter <2.5 μm in diameter ($PM_{2.5}$) and maximum 8-h average ozone in 2023 were sourced from the environmental monitoring centres of each county. The surface elevation data were obtained from ETOPO 1 Arc-minute global relief model.[15]

Statistical analysis

This study employed a two-stage approach to examine the relationship between high temperature and the incidence of acute CVD. In the first stage, we applied a distributed lag non-linear model (DLNM)[16] to assess the county-specific effects of daily maximum temperatures on acute CVD incidence. A cross-basis function has been refined to integrate exposure–response and lag–response associations. To address overdispersion, we employed quasi-Poisson regression models, adjusting for confounders such as $PM_{2.5}$, relative humidity, seasonality, and day-of-week effects. A natural cubic spline with four degrees of freedom (*df*) was used for both temperature exposure and lag effects.

In the second stage, risk estimates from individual counties were pooled to obtain an overall estimate. A two-level random-effects model was constructed to capture both between- and within-province variability by nesting counties within their respective provinces. We computed best linear unbiased predictions (BLUPs)[17] at the county level using the multilevel model. This approach enables geographically clustered counties within the same province to share information effectively with each other.

The BLUP values were used to determine the minimum incidence temperature (MIT) for each county and at the national level. The MIT corresponds to the temperature associated with the lowest risk of CVD incidence, providing critical insights for identifying vulnerable populations and guiding public health interventions aimed at mitigating heat-related health risks.

To examine the delayed effects of high temperature, we analysed lag periods ranging from lag 0–2 to lag 0–7 days and used the lag period with the largest cumulative effect in the model. Furthermore, we performed stratified analyses to explore the differential effects of high temperature on various demographic groups. Specifically, we compared the impacts of extreme heat across genders, age groups, urban vs. rural populations, and climate zones.

A series of sensitivity analyses were also performed to assess the robustness of the findings. First, we tested alternative definitions of extreme heat, using the 90th, 92.5th, and 99th percentiles of daily maximum temperatures. Second, given that previous studies have shown that ozone[18] and altitude[19] may modify the effect of temperature on CVD, we additionally introduced ozone and altitude as linear terms in the main model. Furthermore, we varied the *df* for meteorological variables from 3 to 5 to check if there was any change in the results.

To quantify the heat-related burden of incident acute CVD, we followed the methodology that Gasparrini *et al.*[20] developed to calculate AF and AN. Attributable fraction was computed as

$$AF_x = 1 - \exp(-\beta x)$$

and AN was calculated as

$$AN_x = n \cdot AF_x$$

where n is the total number of CVD onset cases and βx represents the exposure–response coefficient for a given temperature x. Two temperature ranges were considered: (i) all heat, referring to the temperature effects above the MIT, and (ii) extreme heat, referring to temperatures above the 95th percentile of the daily maximum temperature distribution. Subgroup analysis was performed for AF, and empirical confidence intervals (CIs) (95%) were calculated through 1000 Monte Carlo simulations, assuming a multivariate normal distribution of the BLUP.[21]

All statistical analyses in this study were carried out using the 'dlnm' and 'mixmeta' packages in R version 4.4.0. Continuous variables were described as means ± standard deviation (SD) and categorical variables as frequencies and percentages. All tests were two-sided, and a *P*-value of less than 0.05 was considered statistically significant.

Results

Demographic characteristics

In this study, we analysed 856 357 incident acute CVD cases. The majority of cases were male, comprising 58.82% ($n = 503\,780$). In terms of age distribution, 68.65% ($n = 587\,973$) were elderly (aged ≥65 years). The overwhelming majority cases were of Han ethnicity, accounting for 97.60% ($n = 835\,907$). Almost half (48.97%, $n = 410\,682$) were from rural areas. The cardiovascular outcomes monitored included acute stroke (79.36%, $n = 679\,436$) and acute CHD (20.64%, $n = 176\,921$) (*Table 1*).

Given China's extensive geographical diversity, cases were distributed across various climate zones with distinct characteristics. Nearly half (41.92%, $n = 358\,892$) occurred in temperate monsoon climate, characterized by moderate temperatures and seasonal rainfall. Another 54.12% ($n = 463\,267$) occurred in subtropical monsoon climate, marked by hot and humid summers. A smaller proportion of cases were located in tropical monsoon climate (0.98%, $n = 8399$) and in temperate continental climate (3.00%, $n = 25\,688$).

In China, across all study counties in 2023, the mean daily maximum temperature was 22.01°C (ranged from −30.03 to 41.09°C), with

Table 1 Demographic characteristics and cardiovascular disease outcomes of the study population

Characteristics	Female $n = 352\,577$ (%)	Male $n = 503\,780$ (%)	Total $n = 856\,357$(%)	P-value
Age				
18–64	81 159 (23.02)	187 225 (37.16)	268 384 (31.35)	
≥65	271 418 (76.98)	316 555 (62.84)	587 973 (68.65)	<0.001
Ethnic				
Han	344 968 (97.84)	490 939 (97.45)	835 907 (97.60)	
National minority	7609 (2.16)	12 841 (2.55)	20 450 (2.40)	<0.001
Urbanity				
Urban	177 252 (50.27)	268 423 (53.28)	445 675 (52.03)	
Rural	175 325 (49.73)	235 357 (46.72)	410 682 (48.97)	<0.001
Career				
White collar	12 099 (3.43)	24 180 (4.80)	36 279 (4.23)	
Administrator	3702 (1.05)	13 075 (2.60)	16 777 (1.96)	
Blue collar	3864 (1.10)	5526 (1.10)	9390 (1.10)	
Other	221 880 (62.93)	306 746 (60.89)	528 626 (61.76)	
Missing	111 032 (31.49)	154 253 (30.62)	265 285 (30.96)	<0.001
Marital status				
Married/remarried/living together	214 743 (60.91)	324 193 (64.35)	538 936 (62.98)	
Separated or divorced	1481 (0.42)	3790 (0.75)	5271 (0.62)	
Single	3735 (1.06)	12 556 (2.49)	16 291 (1.90)	
Widowed	23 844 (6.76)	12 192 (2.42)	36 036 (4.21)	
Missing	108 774 (30.85)	151 049 (29.98)	259 823 (30.32)	<0.001
Diseases				
CHD	61 447 (17.43)	115 474 (22.92)	176 921 (20.64)	
Stroke	291 130 (82.57)	388 306 (77.08)	679 436 (79.36)	<0.001
Climate zones				
Temperate monsoon climate	150 835 (42.84)	208 057 (41.30)	358 892 (41.92)	
Subtropical monsoon climate	187 545 (53.33)	275 722 (54.62)	463 267 (54.12)	
Tropical monsoon climate	3418 (0.97)	4981 (0.99)	8399 (0.98)	
Temperate continental climate	10 086 (2.86)	15 602 (3.10)	25 688 (3.00)	<0.001

**P*-values represent comparisons between groups for each characteristic.

mean relative humidity of 70.64%, $PM_{2.5}$ concentration of 31.30 μg/m^3, and ozone concentration of 97.86 μg/m^3 (*Table 2*).

Lag pattern of the incidence response at extreme heat

Figure 1 illustrated the lag effects of extreme heat on CVD incidence, with the corresponding effect estimates provided in Supplementary material online, *Table S1*. The cumulative RR of CVD incidence exhibited an initial upward trend, peaking around lag 0–4 days, and then gradually declined. At lag 0–6 days, the RR was 1.10 (95% CI 0.95–1.27), indicating that the elevated risk associated with extreme heat exposure persists for up to 1 week. These findings suggested that the impact of elevated temperatures on CVD incidence was acute, with the highest risk occurring within the initial few days following exposure.

Temperature–incidence relationship cumulated over 4 days

As shown in *Figure 2*, the pooled relationship between temperature and acute CVD incidence demonstrated a non-linear association, cumulated over a 4-day lag period. As the temperature exceeded ~30°C, a notable rise in risk was observed. The pooled RR of CVD incidence associated with extreme heat (95th percentile vs. MIT, ~38.9°C vs.19.3°C) was 1.17 (95% CI 1.05–1.30). Subgroup analysis further showed that the RR of CVD incidence due to extreme heat was higher in individuals aged 65 years and above (RR = 1.20, 95% CI 1.05–1.37, $P < 0.01$), female (RR = 1.19, 95% CI 1.01–1.40, $P = 0.78$), the rural population (RR = 1.18, 95% CI 1.01–1.37, $P = 0.03$), and those living in temperate monsoon/continental climates (RR = 1.25, 95% CI 1.05–1.49, $P = 0.04$), compared with their respective counterparts (*Figure 2* and *Figure 3A*).

Geographical distribution of the minimum incidence temperature (°C)

The geographical distribution of the MITs varied in China (*Figure 4*), ranging from 16.0 to 26.2°C. The MIT distribution showed a clear increasing trend from north to south, with all values exceeding 24°C south of the Tropic of Cancer. This spatial pattern highlighted the variation in temperature-related health risks across different climatic zones in China, with the highest MITs concentrated in tropical regions with warmest climates.

Table 2 Distributions of daily ambient environment conditions in China in 2023

Environmental factors	Mean	Minimum	Q1	Q2	Q3	Maximum
Maximum temperature (°C)	21.00	−30.03	14.20	22.91	29.19	41.09
Relative humidity (%)	70.64	5.80	56.29	75.72	87.99	100.00
$PM_{2.5}$ (μg/m^3)	31.30	1.00	14.50	24.50	39.80	334.90
Ozone (μg/m^3)	97.86	5.90	71.80	91.70	120.10	274.00
Altitude (m)	232.43	1.70	18.30	49.70	244.10	2524.80

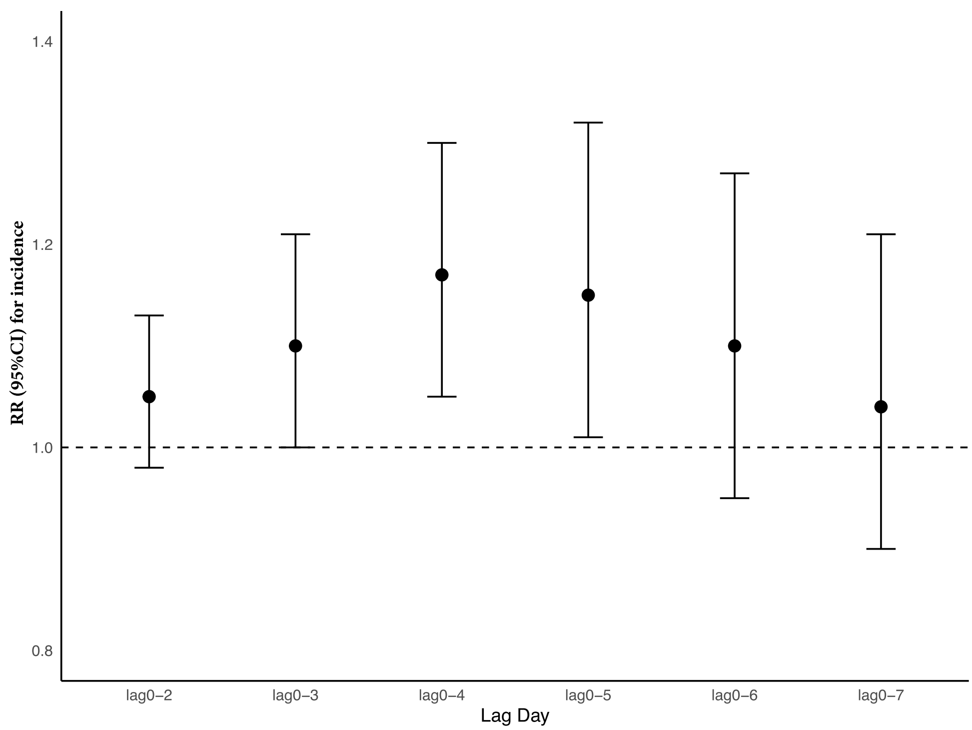


Figure 1 Cumulative lag effects of extreme heat on cardiovascular disease incidence over 1 week. RR, relative risk. The effect of extreme heat was summarized as the relative risk of incidence at the 95th temperature percentiles vs. the minimum incidence temperature.

Burden of acute cardiovascular disease incidence attributable to all heat and extreme heat

In 2023, the AF of acute CVD incidence due to all heat exposures was 3.19% (95% CI 1.34–4.98%), which corresponded to 27 298 CVD onset cases, resulting in a large heat burden. Regarding extreme heat, we found that 0.08% (95% CI 0.02–0.15%) of the total sample occurred during the 5% hottest days of the year, representing 685 CVD onset cases. *Figure 3* illustrated that rural residents and the elderly were more affected by high temperature and experienced a higher health burden of CVD both during all heat and extreme heat (*Figure 3* and Supplementary material online, *Table S2*).

Sensitivity analyses

Sensitivity analyses were performed to validate our main findings. The association between extreme heat and acute CVD incidence remained consistent when using alternative thresholds to define extreme heat, specifically by replacing the 95th percentile of daily maximum temperature with the 90th, 92.5th, and 99th percentiles. Additionally, altering the *df* for meteorological variables from 3 to 5, or extending the main model to include ozone and altitude as covariates to account for potential confounding, did not change the findings substantially, further indicating the robustness of the results (see Supplementary material online, *Table S3*).

Discussion

This study was a national-level investigation in China to investigate the relationship between heat exposure and acute CVD incidence and estimated the heat burden across diverse geographical regions. The study also examined the MIT for CVD incidence, accounting for both cumulative and delayed health impacts. Our primary findings demonstrate

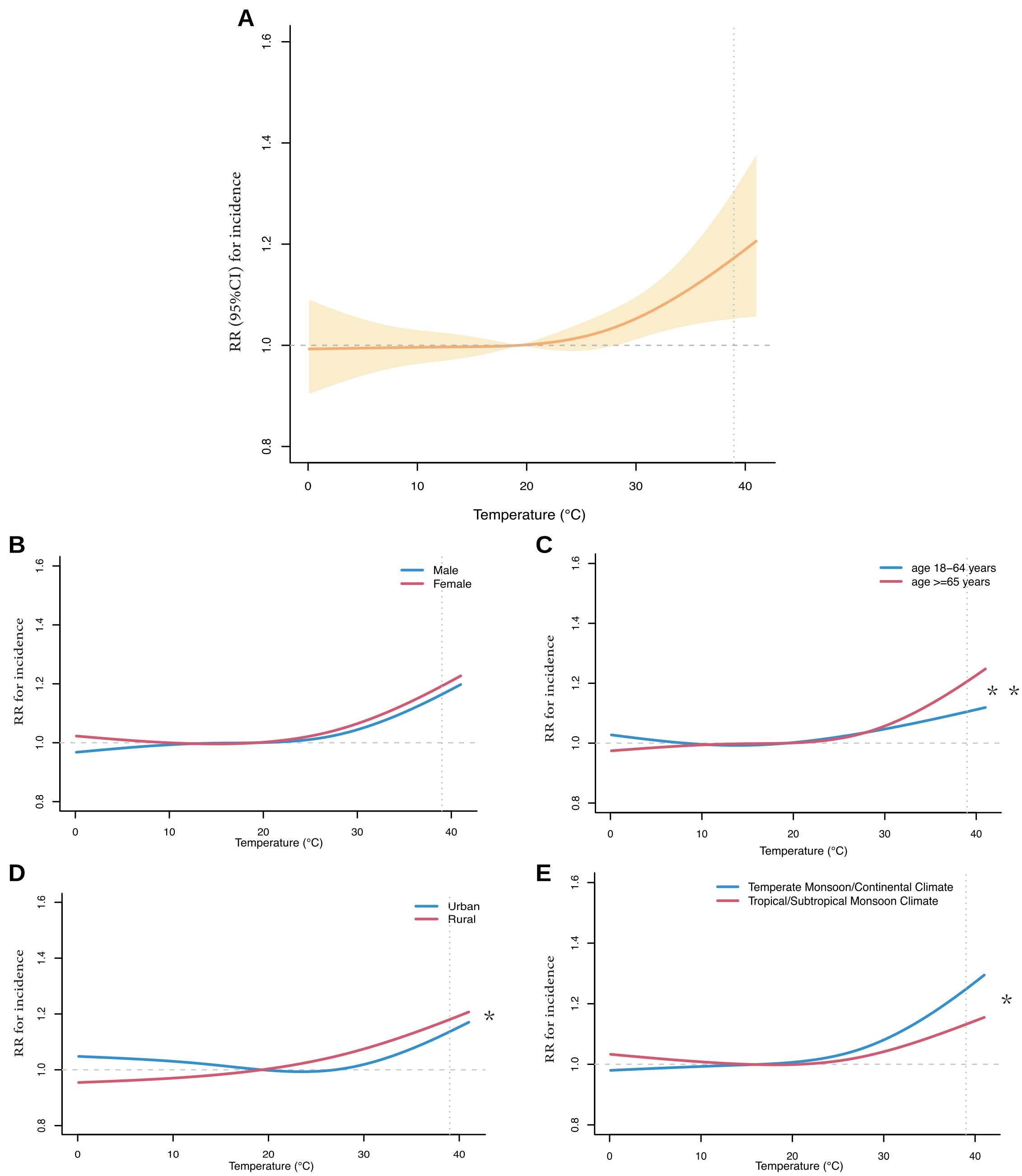


Figure 2 Temperature–incidence relationship and relative risk of cardiovascular disease over a 4-day lag period. (*A*) Pooled non-linear relationship between temperature and cardiovascular disease incidence. (*B*) Relative risk of cardiovascular disease incidence by gender. (*C*) Relative risk of cardiovascular disease incidence by age group. (*D*) Relative risk of cardiovascular disease incidence by urbanicity. (*E*) Relative risk of cardiovascular disease incidence by climate zone. RR, relative risk. Dashed vertical lines in each panel indicate the threshold for extreme heat, defined as the 95th percentile of daily temperature distribution. Asterisk (*) indicates $P < 0.05$, and double asterisk (**) indicates $P < 0.01$ for differences in relative risk between extreme heat and cardiovascular disease incidence.

that extreme heat significantly elevates the risk of acute CVD incidence, with the risk peaking within the first 4 days following exposure. We also found that the heat-related risk and burden varied by age and urbanization level. These results advanced the existing body of knowledge by emphasizing the broader health impacts of extreme heat exposure on incidence. Importantly, our findings highlighted the urgent need for tailored public health interventions, especially in light of ongoing climate change.

Our findings regarding the association between high temperatures and CVD aligned closely with previous research from different climate zones. Achebak *et al.*[12] conducted a quantitative analysis on the association between heat and CVD hospitalizations in Spain, showing that elevated temperatures slightly increased the risk of hospitalization for diseases of arteries, arterioles, and capillaries [RR: 1.104 (1.038–1.175)] and ischaemic heart diseases [RR: 1.083 (1.052–1.114)].

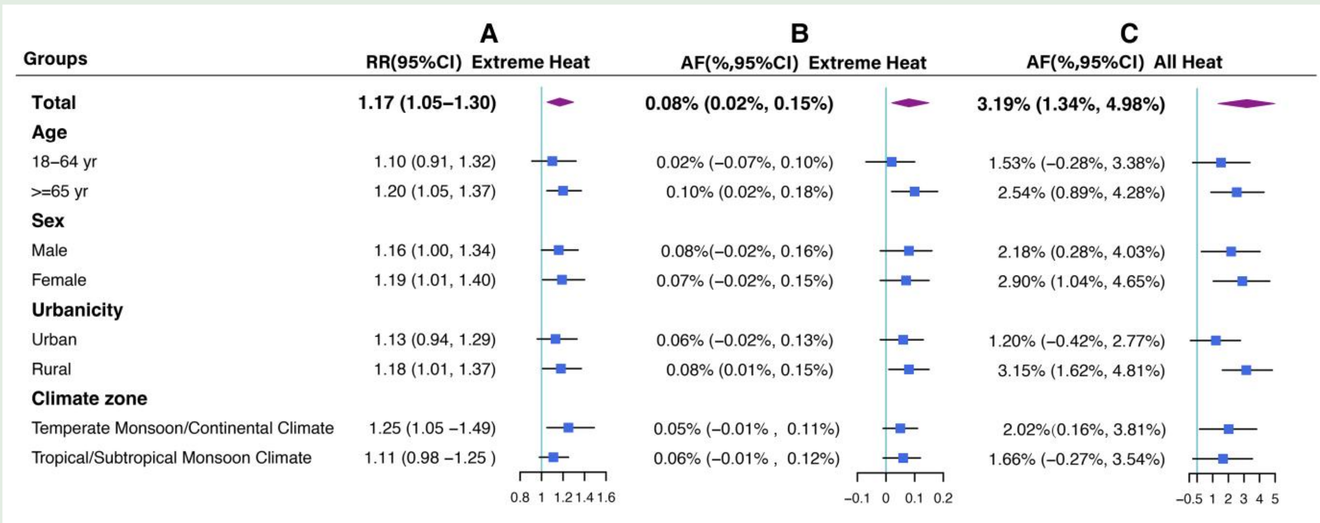


Figure 3 Subgroup analysis by age, sex, urbanicity, and climate zone (*A*) Relative risk and 95% confidence interval of cardiovascular disease incidence associated with extreme heat. (*B*) Attributable fraction and 95% confidence interval of extreme heat exposures. (*C*) Attributable fraction and 95% confidence interval of all heat exposures. RR, relative risk. AF, attributable fraction.

Although the demographic characteristics of patients varied, Achebak's study mainly focused on Whites with a lower proportion of elderly (aged ≥65 years), at 18.9%. Similarly, Tao *et al.*[22] observed that excess hot days were associated with an increased risk of CVD in China [RR: 1.10 (1.05–1.15)]. However, Tao's study was limited to data solely from the largest hospitals in 15 cities, excluding rural areas and other provinces.

Previous studies on heat-related health burden have mainly focused on mortality and all-cause incidence, while few studies so far have specifically examined the heat-related health burden of CVD incidence.[14] Concentrating on all-cause outcomes could dilute the heat–incidence relationship, making it challenging to detect the specific effects of heat.[23] Our study extended this understanding by demonstrating that total and extreme heat contributed to 3.19% and 0.08% of CVD incidence, respectively. Bai *et al.*[24] reported that in Ontario, Canada, 1.2% of CHD hospitalizations and 1.8% of stroke hospitalizations were due to heat exposure, with 0.16% and 0.19% attributable to extreme heat. However, their analysis focused solely on hospitalizations (both new and preexisting cases), excluding outpatient settings such as emergency visits. Another study in Shenzhen, a southern Chinese city, found that 2.5% of first-ever stroke incidence was attributable to heat,[25] underscoring the significant burden of heat on CVD in urban areas. These emphasizes the importance of calculating the AF and AN, which, by translating individual risk (represented by RR) into population-level impact, could be indispensable for public health service evaluation and planning.

Another key finding of this study was the geographic variation in MIT, showing a north–south gradient that likely reflects human physiological,[26–28] behavioural, and cultural adaptations to the local climate.[29] Individuals in tropical regions, accustomed to consistently warmer climates, generally exhibit higher MITs, while those in northern areas were more susceptible to the heat's effects. This corresponds with our subgroup analysis, which showed that populations in northern climate zones had higher risk compared with those in more southern climate zones. Although no previous studies have specifically examined the MIT for CVD, similar trends were observed in studies of the minimum mortality temperature. A study found that countries with hotter climates or close proximity to the equator tend to have higher minimum mortality temperatures, suggesting a degree of population adaptation to local climatic conditions.[30] Yin *et al.*[31] analysed 420 locations and found that minimum mortality temperatures closely aligned with the most frequently observed local temperatures during the same period. This correlation highlights how long-term climate exposure shapes physiological and behavioural adaptations to environmental conditions. Recognizing these geographic differences highlights the importance of incorporating regional climate characteristics into public health strategies.

Our findings confirmed that extreme heat exerts acute and short-term lag effects on cardiovascular health. Consistent with existing literature from China, we observed that the heat effect on CVD was immediate and can persist for up to ∼1 week following exposure.[32,33] This lag effect indicated that individuals might remain at heightened risk for CVD even after extreme heat had dissipated, underscoring the necessity for timely public health interventions during heatwave events and continued monitoring in the days afterwards.

The findings of our study were in line with previous meta-analyses,[34,35] which demonstrate that the association between heat and CVD varied by population characteristics and geographical location. Subgroup analyses further revealed disparities in the effects of extreme heat across different demographic and regional groups. Older individuals appeared to be at greater risk, likely due to physiological differences in thermoregulation. Elderly individuals were more vulnerable because of age-related impairments in temperature regulation and the increased prevalence of comorbidities, which amplified their susceptibility to heat-related health impacts.[29,36] Rural populations also appeared more vulnerable to extreme heat, likely due to limited access to healthcare services and greater exposure to outdoor work. Specifically, many rural residents in China are farmers or labourers and live in underdeveloped housing,[29,37] which can exacerbate heat exposure. In 2023, the average number of air-conditioning units in rural areas was 105.7 units per 100 households, significantly lower than the 171.7 units per 100 households in urban areas.[38]

Our findings are supported by physiological plausibility. Exposure to extreme heat induces various stress responses in the cardiovascular

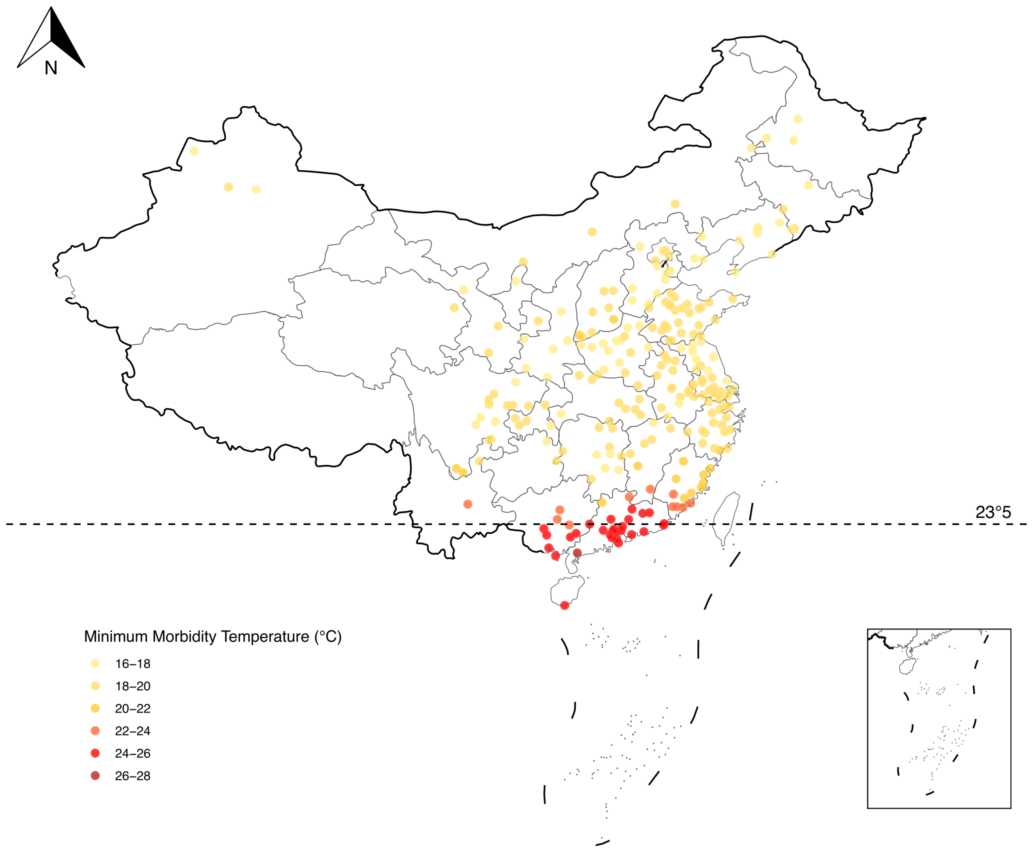


Figure 4 Geographical distribution of minimum incidence temperature across China.

system. To dissipate heat, the body activates mechanisms such as increased skin blood flow and sweating, which elevate cardiac output to maintain blood pressure and support thermoregulation.[39,40] Dehydration caused by extreme heat further exacerbates cardiovascular stress by reducing blood volume and decreasing the heart's filling pressure, which can lead to ischaemia or infarction.[41] Heat exposure can trigger an inflammatory response, with mediators such as cytokines disrupting cellular homeostasis and impairing organ function, thereby exacerbating damage to vulnerable tissues and organs.[42] In addition, extreme heat may also impact cardiovascular health through indirect behavioural and psychological pathways. The E(e)SEEDi lifestyle framework integrates environmental exposures with four core domains of health—sleep, emotion, exercise, and diet.[43] According to this framework, environmental stressors such as extreme heat can compromise the quality of these essential lifestyle factors, thereby increasing cardiovascular vulnerability.

Although this study focused on the adverse effects of extreme ambient heat exposure, it is important to acknowledge that not all forms of heat exposure are harmful. For instance, controlled and time-limited exposures such as Finnish sauna bathing have been associated with cardiovascular benefits, including improved vascular function, reduced blood pressure, and lower risk of cardiovascular events and mortality.[44]

This study has several notable advantages. First, it stands as one of the largest studies to date to examine the effects of extreme heat on CVD incidence in China, covering multiple counties across a range of climate zones. Such extensive cases, combined with broad geographic coverage, allow for a more comprehensive and robust assessment of the relationship between high temperature and CVD risk. Secondly, this study explored MIT variations across different climate zones, providing novel insights into CVD prevention and serving as a valuable reference for region-specific public health interventions. Additionally, few studies have conducted subgroup analyses that differentiate urban and rural populations,[6,12,45] and this study addressed this gap. By identifying specific vulnerable groups, such as rural residents and elderly individuals, this study contributed to the design of targeted adaptation strategies for more effective health outcomes.

However, this study has several limitations. First, as an ecological study, this study was subject to ecological fallacies, and caution was needed when generalizing the findings to other contexts or regions. Second, although we controlled for environmental confounding factors such as humidity and air pollution, individual-level factors such as lifestyle and behaviour still influence the results. Additionally, since most individuals spent the majority of their time indoors,[46,47] relying on outdoor temperature observations might not fully reflect actual heat exposure at the individual level. Beyond coronary heart disease and stroke, extreme heat may also increase the risk of other major adverse cardiovascular events (MACEs), including arrhythmias and heart failure. However, as these conditions are not included in the current scope of the CVD surveillance system in China, they were not assessed in this analysis. Furthermore, the study was based on data from one single year, limiting its ability to assess long-term trends over time. Future research should address these limitations by incorporating more precise individual-level exposure data, exploring compound exposure to other environmental risk factors, using composite biometeorological indicators such as net effective temperature,[48] and examining long-term trends across diverse global contexts to provide a more comprehensive understanding of heat-related cardiovascular risks.

In conclusion, our study demonstrated that extreme heat significantly elevated the risk of acute CVD incidence in China, with notable variations across geographic regions and demographic groups. These findings underscore the urgent need of implementing targeted measures to mitigate heat exposure, particularly for vulnerable populations. For example, establishing early warning systems and enhancing public awareness can enable communities to better anticipate and respond to extreme heat events. And developing tailored interventions to reduce heat exposure for high-risk populations is essential. Together, these strategies provide a comprehensive approach to reduce the adverse health effects of extreme heat on the Chinese population, mitigate CVD risk, and enhance community resilience in the context of ongoing climate change.

Supplementary material

Supplementary material is available at *European Journal of Preventive Cardiology*.

Author contribution

Z.W. had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Z.W.: conceptualization, data curation, methodology, review & editing, supervision, and funding acquisition. X.P.: methodology, formal analysis, and writing—original draft preparation, H.T.: methodology and writing—original draft preparation. C.Z., Y.Z., M.S., Q.J., S.L., X.W., Ye Tian, X.C., Yixin Tian, X.Y., N.T., C.C., Y.Z., F.L., and J.Y.: investigation.

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Data availability

The health data underlying this article will be shared on reasonable request to the corresponding author. The environmental data used in this study are publicly available from their respective sources. The daily meteorological observations from over 2400 meteorological stations were obtained from the China Meteorological Data Sharing Service System (CMDC, available at http://data.cma.cn). Air pollution data were sourced from the environmental monitoring centres of each county in China (available at https://quotsoft.net/air/). Surface elevation data were derived from the ETOPO 1 Arc-minute global relief model, provided by the National Centers for Environmental Information (NOAA NCEI, available at https://www.ncei.noaa.gov/products/etopo-global-relief-model).

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