

Individual and combined effects of heatwaves, air pollution, green spaces, and blue spaces on depressive symptoms incidence

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ABSTRACT:

The health hazards of climate-driven temperature have been extensively studied, but the specific effects on mental health, especially given the backdrop of air pollution and blue-green accessibility, remain largely unknown. Here we investigate individual and synergistic effects of heatwave, air pollution, and blue-green space on depressive symptoms, using data from the China Health and Retirement Longitudinal Study (CHARLS). Logistic regression analyses revealed that exposure to heatwaves was associated with a 4.2 - 14.0% increase in depression risk. Furthermore, for every 10 $\mu\text{g}/\text{m}^3$ increment in ambient concentrations of $\text{PM}_{2.5}$, PM_{10} , CO, and SO_2 , the odds ratios (ORs) of depression increased by 25%, 13%, 1%, and 55%, respectively. We also found positive interactions between the concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and the lack of blue and green spaces with heatwave exposure, both on multiplicative (ORs for product terms >1) and additive (RERIs >0) scales. Simultaneous exposure to heatwave and air pollution or lack of green and blue spaces showed increased risk of depression symptom than exposure alone. This study advocates integrating heatwaves, air pollution, and blue/green infrastructure into climate-resilient mental health policy-making.

Keywords: Heatwave, Air pollution, Blue space, Green space, Depressive symptom

1. Introduction

Climate change has led to a discernible upward trend in the duration, frequency, and severity of extreme heat events globally, exposing more people to the dangers of high temperatures(Bell, Gasparrini, & Benjamin, 2024). Long-term exposure to intense heat can trigger a variety of health issues, such as dehydration, heat exhaustion, heatstroke, and negative effects on pregnancies(Ebi et al., 2021; Sorensen & Hess, 2022). Moreover, high temperatures can also raise the risk of hospitalization and death from an array of illnesses, encompassing heart and kidney conditions, diabetes, and respiratory diseases(Cheng et al., 2024; Moon, 2021; Yan et al., 2023). While the detrimental outcomes of persistently high temperatures are considerable, there is a tendency to overlook the long-term effects on individuals' mental well-being, especially in developing nations. Biological studies provide some clues that high temperatures can impact not only the levels and equilibrium of the neurotransmitter's serotonin and dopamine, but also cause neuroinflammation and cause mental disorders(Barron, Hafizi, Andreazza, & Mizrahi, 2017; S. Lee, Lee, Myung, Kim, & Kim, 2018). The elderly are especially vulnerable to heat-related harm, on account of their decline in cardiovascular function and thermoregulatory capacity(Paneni, Diaz Cañestro, Libby, Lüscher, & Camici, 2017). In the face of the dual challenges of an aging population and climate change, it's imperative to gain a deeper comprehension of the impact of high temperatures on the mental health in middle-aged and older adults, and to identify effective coping strategies.

In addition to heatwaves, the link between air pollutants and depression is biologically plausible(Radua et al., 2024; T. Yang, Wang, Huang, Kelly, & Li, 2023). In practice, the health

impacts of environmental factors are not isolated from one another. For instance, recurrent heatwaves could rise the level of PM_{2.5} due to thermal stress and the associated risks might intensify with the further rise of temperatures(Schaefer, Ebrahimi Salari, Köckler, & Thinh, 2021). Two studies have discovered a combined effect of air contaminants and heatwaves on the occurrence of preterm birth, which is greater than individual effect(Sun et al., 2020; Wang et al., 2020). Another study demonstrated that heatwave exposure could exacerbate the impact of PM_{2.5} on hospitalization risk for schizophrenia, with this interaction varying based on heatwaves' severity and duration(Pan et al., 2024). Nevertheless, the combined influence of heatwaves and air contaminants on depressive symptoms remains to be explored.

In contrast to air pollution, green spaces serve as a protective buffer against heat. Prior findings have underscored the advantageous role of green areas in alleviating extreme heat conditions, lowering mortality risks, and diminishing other detrimental health effects associated with heatwaves(Song et al., 2022; H. Zhang et al., 2021). However, there is insufficient epidemiological data on how green spaces and heatwaves interact to affect depression. Similarly, blue spaces like rivers and coasts can lessen heat impacts due to their capacity for heat absorption and cooling effects like evaporation(Ampatzidis & Kershaw, 2020). Existing researches about the interaction between blue spaces and heatwaves were mainly concentrated on hypertension and mortality, although blue spaces have been proved to ameliorate depressive symptoms (K. Hu et al., 2024; Song et al., 2022; Zhou, Wang, Li, Kadier, et al., 2023). Hence, the role of blue spaces in alleviating the depression risk posed by heatwaves requires further investigation.

To address the gaps in knowledge, this study utilized nationwide cohort data to investigate the individual and joint impacts of heatwaves, air pollutants, and access to blue and green spaces on depressive symptoms in middle-aged and older Chinese populations. This investigation enhances the overall grasp of how heatwaves influence mental health, bolsters the applicability of existing evidence, and fortifies adaptive capacities. It provides scientific insights and directives for crafting healthy and sustainable urban environments.

2. Methods

2.1 Study population

The study was based on data from the China Health and Retirement Longitudinal Study (CHARLS), a national survey focused on the issue of population aging, encompassing data from individuals aged more than 45. The sampling methods and study design have been fully described in prior documentation(Zhao, Hu, Smith, Strauss, & Yang, 2014). Starting with the initial survey in 2011, the project has carried out subsequent follow-up surveys in 2013, 2015, 2018, and 2020. The CHARLS is dynamic cohort and a small number of additional participants were recruited in each follow-up interview (Han et al., 2022). Participants were tracked using unique IDs across different waves. For this research, we used CHARLS data from 2013-2020 for a prospective study, as the data of air pollution in China was unavailable in 2011. Individuals were not included if they (1) were younger than 45 years old, (2) had a baseline diagnosis of depressive symptoms, (3) participated in less than two follow-up visits, or (4) were missing primary variable data (**Fig. 1**). Ultimately, the analysis comprised 12,316 eligible participants across 124 cities in 28 of 31 China's

provinces, and the number of participants across cities ranged from 51 to 211 (**Fig. 2**). It is worth noting that due to privacy protection regulations, personal residential address information is not available. In this case, we assigned environmental exposure values based on the city where the respondents live. Therefore, participants living in the same city have the same level of exposure.

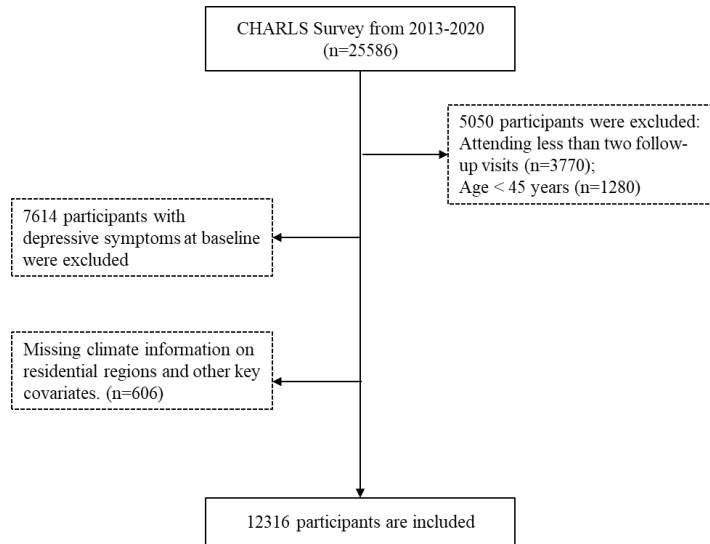


Fig.1 Study flow-chart.

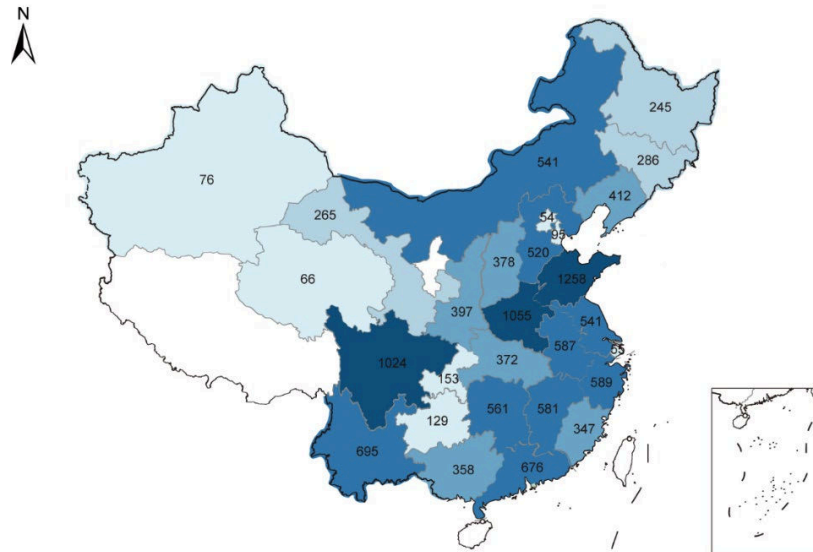


Fig. 2. The distribution of participants.

2.2 Assessment of depressive symptoms

A 10-item questionnaire from the Center for Epidemiologic Studies Depression (CESD) was employed to assess depressive symptoms. Participants were asked to indicate how often they experienced each symptom during the week before the survey. The responses were scored on a four-point Likert scale: 0 (never or seldom; less than one day), 1 (some or a little of the time; 1-2 days), 2 (occasionally or moderately; 3-4 days), or 3 (most or all of the time; 5-7 days). The total score ranges from 0 to 30, with lower scores indicating less severe symptoms. For this research, a score of 10 or above was set as the criterion for identifying individuals with depressive symptoms, a benchmark that has demonstrated high sensitivity and specificity in elderly Chinese population according to previous studies(Liu, Chen, & Yan, 2020; Luo, Guo, Thapa, & Yu, 2021).

2.3 Heatwave definitions

The daily maximum temperature data from 2012 to 2020 for 482 meteorological monitoring stations across China were provided by the United States Air Force Weather Agency (<https://www.ncdc.noaa.gov/isd>). Consistent with prior studies,(H. Zhang et al., 2021; Zhou, Wang, Li, Kadier, et al., 2023) we gathered daily maximum temperature records during the warm season (May 1st to September 30th) and attributed these records to participants by city. Cities without a meteorological station were given the data from the nearest one. The current study lacks a universally accepted definition of heatwaves. We used nine different heatwave definitions from past studies, labeled HW1 to HW9 (Table 1). For example, HW1 is defined as days where

the daily maximum temperature exceeds the 92.5th percentile of the city-specific threshold for the warm season and lasts for at least two consecutive days. Heatwave exposure was defined as "heatwave days" in our study, which were the days exceeding the threshold and lasting for a defined duration. A one-year exposure time window was frequently employed to assess heatwave exposure in previous studies (Mou et al., 2024; Tuerdi et al., 2025; Zhou, Wang, Li, Zhang, et al., 2023). Therefore, we quantified heatwave exposure as the count of heatwave days in the one year preceding depressive symptoms emergence or study completion.

Table 1 Nine types of heatwaves definitions in the present study.

Heatwave definition	Threshold percentile (°C)	Duration (Day)
HW1	92.5th (34.30)	2
HW2	92.5th (34.30)	3
HW3	92.5th (34.30)	4
HW4	95th (34.85)	2
HW5	95th (34.85)	3
HW6	95th (34.85)	4
HW7	97.5th (35.54)	2
HW8	97.5th (35.54)	3
HW9	97.5th (35.54)	4

2.4 Air pollution exposure

Concentrations of ground-level pollutants CO, SO₂, PM_{2.5}, and PM₁₀ were derived from the ChinaHighAirPollutants (CHAP) dataset, which is accessible to the public at <https://weijing-rs.github.io/product.html>. The CHAP data was created employing the space-time extremely randomized trees model, incorporating various data sources including satellite retrievals, land-use information, emission inventories, meteorological conditions, topographical details, and aerosol

optical depth (AOD). AOD data was extracted from moderate-resolution imaging spectroradiometer images using atmospheric correction techniques at different angles. In this study, we used the annual average concentrations of PM_{2.5} (Wei et al., 2020; Jing Wei et al., 2021) and PM₁₀ (J. Wei et al., 2021) at a spatial resolution of 0.01° (about 1 km) as well as the annual average concentrations of SO₂ (Wei et al., 2023), and CO (Wei et al., 2023) at 0.1° (roughly 10 km) were employed in this analysis. When evaluating air pollution exposure, we used the annual average concentration during the year preceding depressive symptoms onset or follow-up completion.

2.5 Exposure to green and blue spaces

The degree of vegetation cover was measured by Normalized Difference Vegetation Index (NDVI). The annual city-level NDVI data, which is synchronized with heatwave exposure, came from the Moderate-resolution Spectroradiometer (MODIS) on National Aeronautics and Space Administration's Terra satellite (with a spatial resolution of about 0.005°). The NDVI values ranged from -1 to 1, where higher values signified more extensive vegetation. Similarly, we calculated the average NDVI values in the year prior to depressive symptoms onset or the end of follow-up. The downloading and processing of NDVI values were completed through Google Earth Engine (GEE), while the extraction was carried out using ArcGIS 10.6.

The proportion of open water bodies in a city is an indicator of exposure to blue spaces. In this study, we used the annual land cover dataset with 0.05° spatial resolution in China (1992-

2018), which was publicly released by the National Earth System Science Data Center, National Science & Technology Infrastructure of China (<http://www.geodata.cn>). Briefly, the dataset was generated by converting the original land cover classifications from the European Space Agency (ESA) and the Climate Change Initiative (CCI) (<https://www.esa-landcover-cci.org/>) into plant functional types (PFTs). This conversion involved matrix transformation and sliding window algorithms to quantify the percentage coverage of each land cover type (Ji et al., 2020; Zhu et al., 2019). Subsequently, 15 distinct land use categories with a spatial resolution of 0.05° were identified based on PFT, and the proportion of each PFT in the grid pixels was summarized. We also defined blue space exposure as the mean fraction of open water areas in urban grid cells during the year preceding depressive symptoms emergence or the follow-up termination. Although the data for 2019 were lacking, given that the overall change in the blue space exposure indicator was not significant, we used the data from the previous follow-up to substitute for the 2019 data in our analysis.

2.6 Covariates

Based on existing studies, we identified a set of covariates for our analysis. The demographic variables included age and gender (female and male). The socioeconomic variables comprised marital status (Never married, Divorced/separated/widowed, and Married/partnered), education level (Middle school or above, Primary school or below), income (Income zero, Income positive), employment status (Unemployed, Employed), and urbanicity (Rural and Urban). Health behavior factors encompassed smoking habits (Smoker or Non-smoker) and drinking habits (Drinker or

Non-drinker). Social engagement (participating, not participating) was also considered.

2.7 Statistical analysis

Baseline characteristics and environmental indicators during follow-up were presented as means with standard deviations (SD), proportions, or medians (IQR). In our study, environmental exposures, such as heat wave, air pollutants, and sociodemographic characteristics, such as age, education level, drinking state, income, violated the proportional hazards assumption of Cox proportional hazards model even after statistical processing. In consequence, we employed logistic regression model in our study and presented odds ratios (OR) with their corresponding 95% confidence interval (CI), which has also been justified by numerous researches conducted in CHARLS. In the primary analysis, we assessed the independent impact of heatwaves, air contaminants, and insufficient exposure to blue and green spaces on the likelihood of depressive symptoms (Chen et al., 2024; X. Hu et al., 2023; K. Yang & Chen, 2024). Heatwave exposure was modeled both as a continuous variable (per day unit increase) and a binary variable (experienced and not experienced heatwaves). Additionally, air pollutant concentrations, NDVI, and blue spaces were analyzed as continuous and quartile-based categorical variables. We then explored the link between heatwave exposure and depressive symptoms across subgroups defined by gender, age, and educational level.

In the second stage, to investigate the potential combined effects of heatwave exposure, air pollution, blue space, and green space exposure on depressive symptoms, this study employed both multiplicative and additive interaction analyses. Specifically, we introduced a cross-product term

to assess the multiplicative interactions among these environmental factors and calculated the relative excess risk due to interaction (RERI) to quantify their additive impact on depressive symptoms. In these analyses, exposures to heatwave, air pollution, NDVI, and blue spaces were also presented in both categorical and continuous forms. For classification rule, heatwave exposure was categorized into two groups: those who have experienced heatwaves and those who have not. Then, air pollution, NDVI, and blue spaces were also divided into two categories based on the median values: below the median and at or above the median. The calculation of RERI helps us understand how the combination of these environmental factors affects depressive symptoms. The $RERI > 0$ indicates an additive interaction effect where the combined influence of factors exceeds their individual impacts due to synergy. Conversely, the $RERI < 0$ suggests that the interaction is less than additive, indicating an antagonistic effect. For categorical and continuous forms of exposures, we used Delta and Bootstrap methods to calculate the confidence intervals for RERIs, respectively. We also looked into how individual characteristics like gender, age, and education might modify the interactive effects. Finally, we performed stratified analyses based on heatwave exposure to explore the link between air pollutants, blue spaces, and green spaces with depressive symptoms.

Four sensitivity analyses were performed here. Firstly, all individual effect analyses were repeated using a general linear model for depressive symptoms scores as a continuous variable outcome. Secondly, recognizing the influence of physical health on mental well-being, we made additional adjustments for medical histories. This included accounting for self-reported baseline

conditions such as asthma, stroke, hypertension, diabetes, arthritis, cardiac issues, digestive disorders, liver conditions, pulmonary diseases, and kidney ailments, to manage potential confounding factors. We categorized health conditions into three categories: none, one, or multiple. Thirdly, we excluded those with depressive symptoms within the first two years of follow-up to mitigate the impact of reverse causation in our analysis. Finally, considering the differences of economy and lifestyle across geographical locations, we further adjusted for seven the seven regional categories of China (Northeast, North, Central, Eastern, Southern, Northwest, Southwest). All statistical analyses were performed using R version 4.2.1 (R Development Core Team).

3. Results

3.1 Characteristics of the study population

Table 2 provided descriptive statistical analysis of the basic characteristics and environmental exposures of the study participants. During a median follow-up of 5 years, 5,807 new cases of depressive symptoms were identified, with an incidence of 47.2%. The average age of the participants was 57.77 years (SD = 9.41). Among all participants, 46.94% were female, and 48.73% and 44.65% were current alcohol drinkers and smokers at baseline, respectively. The medians (IQRs) of air pollution, blue and green spaces from 2013 to 2020 were as follows: PM_{2.5}, 45.90 µg/m³ (25.00 µg/m³), PM₁₀, 76.50 µg/m³ (44.50 µg/m³), CO, 911.86 µg/m³ (336.27 µg/m³), SO₂, 14.31 µg/m³ (12.30 µg/m³), the proportion of blue space, 1.02% (2.25%), NDVI, 0.52

(0.16). We observed that among the participants with depressive symptoms, more had experienced personal heatwave events during the follow-up. The map in Fig. 2 showed the geographic distribution of these participants.

Table 2 Basic characteristics of participants according to depressive symptoms.

Characteristics	Total (n = 12316)	CES-D<10 (n = 6509)	CES-D≥10 (n = 5807)
Age (years), Mean ± SD	57.77 ± 9.41	57.92 ± 9.69	57.59 ± 9.09
Gender, n (%)			
Male	6535 (53.06)	3856 (59.24)	2679 (46.13)
Female	5781 (46.94)	2653 (40.76)	3128 (53.87)
Urbanicity, n (%)			
Urban	5213 (42.33)	3076 (47.26)	2137 (36.80)
Rural	7103 (57.67)	3433 (52.74)	3670 (63.20)
Education Level, n (%)			
Primary school or below	7969 (64.70)	4055 (62.30)	3914 (67.40)
Middle school or above	4347 (35.30)	2454 (37.70)	1893 (32.60)
Marital status, n (%)			
Married/partnered	11201 (90.95)	5936 (91.20)	5265 (90.67)
Divorced/separated/widowed	1046 (8.49)	549 (8.43)	497 (8.56)
Never married	69 (0.56)	24 (0.37)	45 (0.73)
Employment status, n (%)			
Unemployed	3547 (28.80)	1957 (30.07)	1590 (27.38)
Employed	8769 (71.20)	4552 (69.93)	4217 (72.62)
Income, n (%)			
No	8703 (70.66)	4440 (68.21)	4263 (73.41)
Yes	3613 (29.34)	2069 (31.79)	1544 (26.59)
Smoking status, n (%)			
Non-smoker	6817 (55.35)	3359 (51.61)	3458 (59.55)
Smoker	5499 (44.65)	3150 (48.39)	2349 (40.45)
Drinking status, n (%)			
Non-drinker	6315 (51.27)	3122 (47.96)	3193 (54.99)
Drinker	6001 (48.73)	3387 (52.04)	2614 (45.01)
Social activity, n (%)			
No	5375 (43.64)	2760 (42.40)	2615 (45.03)
Yes	6941 (56.36)	3749 (57.60)	3192 (54.97)
Air pollutants (µg/m ³), median (IQR)			

Characteristics	Total (n = 12316)	CES-D<10 (n = 6509)	CES-D≥10 (n = 5807)
PM _{2.5}	45.90 (25.00)	43.30 (24.10)	49.60 (29.10)
PM ₁₀	76.50 (44.50)	71.70 (44.50)	82.70 (44.30)
CO	911.86 (336.27)	889.15 (272.51)	956.29 (392.11)
SO ₂	14.31 (12.30)	12.38 (8.33)	16.90 (15.96)
NDVI, median (IQR)	0.52 (0.16)	0.52 (0.16)	0.53 (0.16)
Blue space (%), median (IQR)	1.02 (2.25)	1.10 (3.04)	0.93 (2.06)
Participants who experienced heatwave, n (%)			
HW1 (92.5th-2D)	12206 (99.11)	6434 (98.85)	5772 (99.40)
HW2 (92.5th-3D)	10607 (86.12)	5405 (83.04)	5202 (89.58)
HW3 (92.5th-4D)	7210 (58.54)	3685 (56.61)	3525 (60.70)
HW4 (95th-2D)	11370 (92.32)	5845 (89.80)	5525 (95.14)
HW5 (95th-3D)	7092 (57.58)	3396 (52.17)	3696 (63.65)
HW6 (95th-4D)	2932 (23.81)	1397 (21.46)	1535 (26.43)
HW7 (97.5th-2D)	8573 (69.61)	4249 (65.28)	4324 (74.46)
HW8 (97.5th-3D)	2377 (19.30)	1094 (16.81)	1283 (22.09)
HW9 (97.5th-4D)	276 (2.24)	131 (2.01)	145 (2.50)

3.2 individual effects of heatwave, air pollution, and blue and green spaces on depressive symptoms risk

The individual impacts of various environmental factors on depressive symptoms were investigated (**Table S1**). We found that exposure to heatwaves was associated with an elevated risk of depressive symptoms, with ORs (95% CI) ranging from 1.04(1.03–1.05) to 1.14(1.12–1.15). Depressive symptoms risk was significantly heightened by exposure to air pollutants, with SO₂ being particularly impactful. Specifically, for every 10 µg/m³ increase in levels of PM_{2.5}, PM₁₀, CO, and SO₂, the odds ratio of depressive symptoms increased by 25%, 13%, 1%, and 55%, respectively. When analyzing the impact of blue and green spaces on depressive symptoms risk, a decrease in NDVI did not significantly raise the risk of depressive symptoms. Conversely, a

reduction in blue spaces was significantly linked to a higher likelihood of depressive symptoms, with an OR of 1.35 (95% CI: 1.23, 1.48).

3.3 Interaction between heatwave and air pollution on depressive symptoms risk

After evaluating the multiplicative and additive interactions between heatwave in nine definitions and air pollutants, HW5 showed the stronger interaction effects and then was shown in **Figure 3**. Notably, HW5 exhibited significant multiplicative effects in conjunction with PM_{2.5}, PM₁₀, CO and SO₂, the corresponding ORs (95% CI) were 1.81(1.56-2.10), 2.07(1.78-2.40), 1.35(1.17-1.57) and 1.58(1.36-1.83). The additive interaction analysis also showed that a positive additive effect between HW5 and air contaminants, indicating that participants exposed to heatwaves and higher levels of air contaminants were at greater risk of depressive symptoms compared to those with lower pollution exposure and no heatwave experience (RERI > 0). Changing HW5 and air pollution into continuous form showed similar results (**Table S2**). The interactions between heatwave in other eight definitions and air pollutants were shown in **Figure S1**. Subgroup analyses results, as shown in the **Table S3**, indicated that the combined effects of high levels of air pollutants and heatwaves exposure were more significant in individuals aged 45-59 than those aged 60 and above. However, no noteworthy variations were seen among genders and education levels.

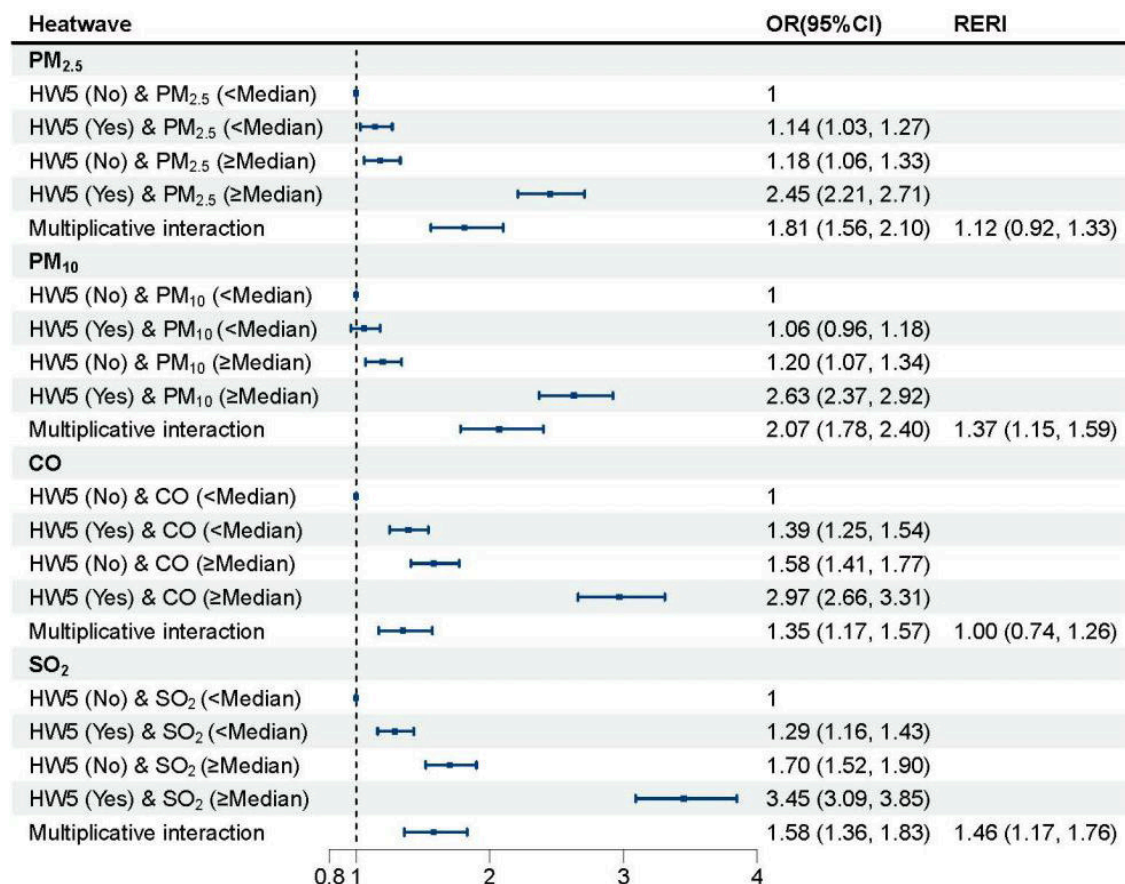


Fig. 3 Multiplicative and additive interaction of air contaminants and heatwaves on the depression. Models were adjusted for age, gender, urbanicity, education level, marital status, employment status, income, smoking status, drinking status, and social activity participation.

3.4 Interaction between heatwave and blue and green spaces on depressive symptoms risk

The strongest interactions between heatwave, blue spaces, and green spaces on depressive symptoms were observed in HW5, which were shown in **Figure 4**. A synergistic interaction was indicated by the positive and statistically significant multiplicative interactions between the

heatwave and the deficiency in green spaces (OR= 1.58, 95%CI: 1.36-1.84), indicating an increase in depressive symptoms risk by 58% when considering the multiplicative effects. For blue spaces, a significant combined effect was observed between lack of blue space exposure and heatwaves (ORs = 1.31, 95% CI:1.13-1.52). The additive interaction analysis corroborated the findings from the multiplicative interactions, showing a consistent pattern of increased depressive symptoms risk under the combined exposure to insufficient blue and green spaces and heatwaves, with RERIs ranging from 0.53 to 0.56. Changing the exposures of heatwave, lack of green space and blue space into continuous forms did not significantly change the results (**Table S2**). The interactions between heatwave in other eight definitions and green and blue spaces were shown in **Figure S2**. The subgroup analysis exclusively reveals a pronounced synergistic effect between heatwave exposure and lack of green space among individuals aged 45-59, as compared to those 60 and older. No significant modifying effects were detected in other subgroup analyses (**Table S4**).

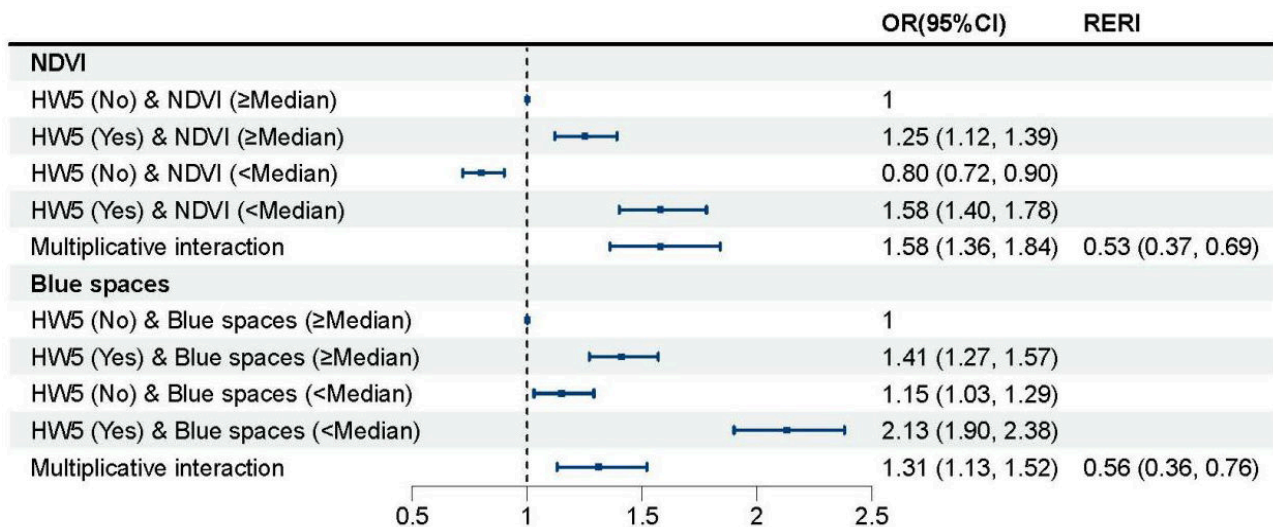


Fig. 4 Multiplicative and additive interaction of heatwaves, green and blue spaces on depression. Models were adjusted for age,

gender, urbanicity, education level, marital status, employment status, income, smoking status, drinking status, and social activity participation.

3.5 Stratified analysis

The stratified analysis results based on exposure to heatwaves, as depicted in **Table 3**, which indicated that individuals who have experienced heatwave exposure exhibited a heightened vulnerability to the impacts of air pollutants, lack of green spaces, and absence of blue spaces. This increased susceptibility correlated with a significantly elevated risk of depressive symptoms for individuals who have been subjected to heatwaves compared to those who have not.

Table 3 Associations of air pollution, lack of blue and green spaces on the incidence of depressive symptoms stratified by exposure to heatwaves.

Heatwave	PM _{2.5}		PM ₁₀		CO		SO ₂		NDVI		Blue spaces	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
No	1	1.18(1.05, 1.32)	1	1.19(1.06, 1.33)	1	1.57(1.40, 1.76)	1	1.69(1.51, 1.89)	1	0.80(0.71, 0.90)	1	1.19(1.06, 1.34)
Yes	1	2.18(1.97, 2.40)	1	2.05(2.67, 2.76)	1	2.16(1.96, 2.38)	1	2.70(2.44, 2.98)	1	1.29(1.17, 1.42)	1	1.50(1.36, 1.65)

Models were adjusted for age, gender, urbanicity, education level, marital status, employment status, income, smoking status, drinking status, and social activity participation

3.6 Sensitivity analyses

In the sensitivity analyses, heatwave, air pollution and lack of green and blue spaces in continuous form showed positive associations with depression score (**Table S5**). Furthermore, a positive link was consistently observed between heatwaves, air pollution, and the lack of blue spaces with depressive symptoms, while no correlation was found between the lack of green spaces and depressive symptoms (**Table S6**). Our robustness checks on the interactive effects confirmed that the joint impact of heatwave, air pollution, and access to blue and green spaces remained significant, with the estimated impact values consistent with our main study findings, including the adjusted regional categories (**Table S7-S9**). Therefore, the sensitivity analyses had no impact on the key findings of our research results.

4. Discussion

This comprehensive study provides fresh perspectives on how multiple environmental factors relate to depression in China. A principal result of our study was the independent contribution of heatwaves, air pollutants, and the lack of blue spaces to the development of depressive symptoms, while no separate effect of the lack of green spaces on depressive symptoms was detected. Alongside a synergistic effect on the incidence of depressive symptoms was observed between high levels of air pollution and heatwaves, the study also revealed that exposure to environments deficient in green and blue spaces during heatwaves synergistically increased the risk of developing depressive symptoms through their interactive effects.

Previous studies had pointed that high temperatures could be a potential risk factor for

depression, leading to a rise in suicide rates and increased hospitalizations and emergency visits for various mental health condition(Mullins & White, 2019; Thompson et al., 2023; S. Zhang et al., 2020). Our research in China confirmed this trend, revealing a significant impact of heatwaves on the incidence of depressive symptoms among middle-aged and elderly people. Unlike previous studies that directly used daily average temperatures or apparent temperatures(S. Lee et al., 2018; Min et al., 2019), our study utilized nine different heatwave definitions to better understand the intensity and duration of heatwaves, thereby mitigating the effects of long-term local adaptation differences among populations in various regions. A substantial amount of research had suggested that air pollutants might negatively affect mental health, which aligned with our results. For instance, research encompassing 75 urban areas in China demonstrated that brief exposure to ambient SO₂, NO₂, PM_{2.5}, CO, and PM₁₀ significantly heightened the likelihood of being hospitalized due to depression(Gu et al., 2020). Analogous findings were reported in a Canadian time-series analysis(Min et al., 2019). Our research did not find a distinct effect of the absence of green spaces on depressive symptoms, which might have warranted further investigation since other studies had reported that enhancing the frequency of exposure to green spaces could ameliorate mental health(Wan et al., 2022; M. Yang, Dijst, Faber, & Helbich, 2020; Z. Zhang, Zhang, Yang, & Zhong, 2023). While green spaces did not independently affect depressive symptom risk, the study did find a significant link between reduced blue spaces and depressive symptom risk, suggesting that access to water features may be a protective factor against the mental well-being impacts of heatwaves(Ghosh & Pal, 2024; Li et al., 2024).

The mechanisms by which heatwaves, air pollution, and blue and green spaces affect depression are multifaceted, involving direct physiological impacts, behavioral changes, and interactions with existing mental health conditions. Initially, high temperatures not only impact neurotransmitters serotonin and dopamine levels and balance but also lead to neuroinflammation(Barron et al., 2017; Mullins & White, 2019; Taylor, Watkins, Marshall, Dascombe, & Foster, 2015). Animal research has demonstrated that exposure to heat could cause significant neuroinflammatory responses and neuronal cell death in the brain's hippocampal region(Chauhan et al., 2017; W. Lee, Moon, Kim, Lee, & Oh, 2015). In addition, high temperatures can cause sleep disturbances and reduce people's willingness to engage in healthy behaviors(Nori-Sarma et al., 2022; Thompson et al., 2023), all of which can lead to depressive symptoms. Although the biological mechanisms linking air pollution to depression remain unclear, existing researches indicated that air pollutants such as particulate matter and sulfur oxides can affect the brain through human inflammatory and oxidative stress pathways(Hahad et al., 2020; G. Yao, Yun, & Sang, 2016). These contaminants may act through the trigeminal nerve, systemic circulation, or olfactory receptor neurons(Block & Calderón-Garcidueñas, 2009), and then trigger neuroinflammation, cause neuroendocrine disorders, and subsequently lead to depression. Blue and green spaces primarily affect our well-being, both physically and mentally, through broader ecosystemic indirect mechanisms such as reducing urban heat island impacts, alleviating air and noise pollution, and preventing flooding(Dzhambov & Dimitrova, 2014; Renterghem, 2019; L. Yao, Yang, Xu, Zhao, & Sailor, 2023). Additionally, green spaces and blue spaces have been found to reduce the affliction

of mental disorders by improving sleep(Vaeztavakoli, Lak, & Yigitcanlar, 2018; W. Yang, Moon, & Kim, 2018), promoting physical activity(Hartig, Mitchell, de Vries, & Frumkin, 2014; Orstad, Szuhany, Tamura, Thorpe, & Jay, 2020) and social interaction(de Vries et al., 2016).

Interaction studies have discovered that concentrations of CO, PM₁₀, PM_{2.5}, and SO₂ might synergize with extreme heat, intensifying the detrimental effects of heatwaves on depressive symptoms. Subgroup analyses further corroborate this interaction, demonstrating that exposure to heatwaves significantly intensifies the detrimental mental health outcomes associated with air pollution. Existing studies suggest that the combined impact of extreme temperatures alongside air contaminants could be detrimental to health. For instance, a cohort study from four countries has discovered the synergistic effect of PM_{2.5} levels and heatwaves on the occurrence of cardiometabolic diseases(Peng et al., 2024). In California, a study has highlighted a significant effect of heatwaves combined with higher air pollution levels, specifically for PM_{2.5}, O₃, and PM₁₀, contributing to the occurrence of preterm birth(Sun et al., 2020). Mechanistically, heatwaves and PM_{2.5} may act through similar biological processes that include the intensification of oxidative stress and systemic inflammation, both contributing to the impairment of brain tissue(Hong et al., 2024; Iba, Helms, Levi, & Levy, 2023; Kelly & Fussell, 2015). Heat-induced enhancement of respiratory tract permeability increases PM_{2.5} alveolar deposition efficiency and hasten the assimilation of air pollutants into the body(Grande et al., 2021; Rahman et al., 2022). For other air pollutants, a multi-national study revealed that the combination of high temperature and pollutants such as PM₁₀, O₃, NO₂, and CO could significantly increase the risk of excess mortality(W. Lee et

al., 2019). Furthermore, a meta-analysis indicated that CO significantly modifies the effect of heat on cardiovascular mortality rates(X. Hu et al., 2022). Therefore, reducing air pollution emissions should be part of strategies to manage the extra health risks from extreme heat. Future research should continue to uncover these complex interactions to inform policy and urban planning, ensuring the public health amidst rising urban pollution and climate change.

Our findings also indicated that insufficient blue and green spaces can synergistically increase the risk of depressive symptoms in conjunction with heatwaves. An increasing body of research had found that access to blue and green spaces can mitigate the health threats posed by extreme heat. A case-crossover study involving 16 cities confirmed that living environments rich in blue and green spaces can significantly lessen the risk of hospitalization for schizophrenia caused by heatwaves(Pan et al., 2024). Echoing this, a case-time series analysis demonstrated that both blue spaces and green spaces can notably lower the risk of cardiovascular mortality associated with high temperatures(K. Hu et al., 2024). Research across 93 European cities projected that more urban tree cover could reduce urban heat island intensity by 0.4°C, potentially preventing 2,644 premature deaths and improving mental health through better environmental conditions(Iungman et al., 2023). Green spaces alleviated the effects of extreme heat by regulating essential ecosystem services like temperature, humidity, and wind speed(Godina et al., 2023; Oliveira, Andrade, & Vaz, 2011; Shen, Zhang, Xin, & Liu, 2022). Furthermore, they promoted health by encouraging socialization, rest, and mental recovery(de Vries et al., 2016; Jennings & Bamkole, 2019; Nordh & Stby, 2013; White, Pahl, Ashbullby, Herbert, & Depledge, 2013). Similarly, blue spaces, attributed

to their capacity to retain heat and interactions with the surrounding environment, could also serve as effective protective buffers against thermal exposure (Georgiou, Morison, Smith, Tiegies, & Chastin, 2021; Jay et al., 2021). As cities continue to grapple with the challenges of urbanization and climate change, the strategic enhancement and preservation of these spaces are paramount. They serve as vital buffers against the adverse health effects of heatwaves, supporting not only the physical well-being but also the mental resilience of urban populations.

This analysis leveraged a sizable nationwide cohort and used various heatwave criteria to better capture the thermal adaptability of local communities. We explored the joint effects of heatwaves, air pollutants, and insufficient blue and green spaces on depressive symptoms, a relatively unstudied area. This study also has some limitations. Firstly, considering the extensive size of Chinese urban areas and the absence of specific address, we relied on environmental exposure in city-level with spatial resolution ranging from 0.005° to 0.1° , which might not capture individual-level variations and result in inaccurate exposure categorization. Secondly, the absence of data on factors like time spent outdoors, household cooling mechanisms, and building characteristics may compromise the precision of our findings. These factors can be influenced by socioeconomic status and could affect exposure to environmental risk and vulnerability to depressive symptoms. Thirdly, further research is needed to explore the impacts of socioeconomic status, which might influence individual access to green and blue spaces. For example, individuals with low socioeconomic status might have difficulty accessing or using these spaces due to high costs of high-quality community, long distance to public park, or other factors. Finally, the potential

for information bias is present, given that depressive symptoms were evaluated through interviews without clinical diagnosis.

5. Conclusion

This research sheds light on the mental health hazards of extreme heat for middle-aged and older people. The findings indicate that heatwaves, air pollution, and lack of blue spaces each independently have a detrimental impact on depressive symptoms. Furthermore, the interactive effects of air contaminants, insufficient blue and green spaces, and heatwaves exposure significantly affect depressive symptoms, both on multiplicative and additive scales. Our results emphasize the necessity of developing public health strategies to curb air pollution, and preserve blue and green spaces, especially during periods of heatwaves.

Author Information

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Ethical approval

Approval for the original CHARLS was obtained from the Biomedical Ethics Review Committee of Peking University (IRB00001052-11015), and all participants signed informed consent at the time of participation.

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 statement

The datasets that support this article are publicly available.

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