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Long-Term Changes in Heatwave-Ozone Compound Events and Spatially Heterogeneous Ozone Associations across China

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ABSTRACT

Heatwaves and surface ozone pollution frequently co-occur during the warm season, posing compound environmental and health risks. However, the long-term evolution of different heatwave types and their influences on ozone pollution remain insufficiently characterized across China. Using CN05.1 daily maximum and minimum temperature data, the ChinaHighAirPollutants surface ozone product, ERA5 reanalysis variables, and selected socioeconomic and environmental indicators, this study examined daytime heatwaves (DHWs), nighttime heatwaves (NHWs), compound day-night heatwaves (CHWs), ozone pollution, and heatwave-ozone compound event days across China during 2000-2024. Conditional probability and risk-ratio analyses were conducted for six regional domains, while multiscale geographically weighted regression (MGWR) was used to characterize spatially varying ozone associations. Results showed significant nationwide increases in all heatwave types, ozone levels, and compound events, with NHWs and CHWs rising faster than DHWs. Ozone pollution exhibited a pronounced east-west gradient, with hotspots in the North China Plain and Yangtze River Delta, and compound events expanded substantially after 2015 beyond traditional hotspots. Heatwaves significantly elevated ozone probability, with DHWs exerting the strongest influence and CHWs prolonging ozone exposure through persistent favorable conditions. Beijing-Tianjin-Hebei region showed the highest conditional ozone probabilities, whereas the Sichuan Basin displayed the largest relative increase compared with non-heatwave conditions. MGWR revealed pronounced spatial heterogeneity: Maximum temperature and solar radiation generally showed positive associations with ozone, while relative humidity showed predominantly negative associations; temperature sensitivity of ozone increases markedly in Beijing-Tianjin-Hebei, Central China, and Eastern China between 2010 and 2020. Overall, climate warming intensifies both heatwave-ozone compound events and climatic sensitivity of ozone pollution, underscoring the need for integrated climate adaptation and air-quality management.

Key words: Heatwave; Ozone pollution; Compound extreme events; Spatiotemporal evolution; Conditional probability; Multiscale Geographically Weighted Regression (MGWR)

1. Introduction

In recent decades, China has witnessed a notable increase in climatic events characterized by extreme heatwaves (Jiang et al. 2023) and elevated ozone pollution levels (Huang et al. 2018), largely driven by the dual forces of rapid industrialization and global climate change. These phenomena are not only considered serious environmental problems, but also increasingly recognized as significant health hazards, contributing to the overall burden of disease within the nation (Watts et al. 2021). Particularly, extreme heatwaves have emerged as one of the most common and devastating natural disasters in China. For example, during the extreme heatwave in southern China in August 2022, the temperature in the Sichuan Basin was abnormally 5°C higher than the average temperature from 1981 to 2010 (Gong et al. 2024). At the same time, some 360 million people were affected by extreme temperatures above 40°C (Mallapaty 2022), posing a huge threat to public health. Over the past two decades, heatwaves have become one of the most deadly climate-related hazards in China. A national-scale assessment attributed approximately 10,000–20,000 annual heatwave-related deaths during 1979–2020, with a marked increasing trend since the 2000s (Chen et al. 2022b), echoing global projections of more frequent and severe heat extremes under continued warming (Ban et al. 2022). He et al. (2021) assessed the current mortality burden and future mortality risk from compound extreme heat in China, providing further evidence of the health threat from extreme weather events.

Simultaneously, extreme heat and weather anomalies associated with global warming are increasingly affecting ozone pollution levels across China. Observational studies have documented a concerning rise in warm-season surface ozone concentrations since the early 2000s (Huang et al. 2018; Lu et al. 2020), driven by both increased precursor emissions and climate-induced meteorological changes (Sillman 1999). In particular, heatwaves have been shown to accelerate photochemical ozone production through elevated temperatures, enhanced biogenic VOC emissions, and stagnant atmospheric conditions (Gong et al. 2024; Kou et al. 2023; Xu et al. 2023). The coupling between ozone and temperature extremes operates through both photochemical and radiative pathways (Mazzarella and Palumbo 1989), and the role of synoptic-scale meteorological conditions in modulating air pollution has been extensively documented in various climatic settings (Stevens and Phillips 2025). Using a coupled meteorology-chemistry model, M. Li et al. (2024b) demonstrated that the record-breaking heatwaves in 2013 and 2022

accelerated photochemical ozone production by boosting both anthropogenic and biogenic emissions, while simultaneously suppressing dry deposition due to water-stressed vegetation, leading to more than a 30% increase in ozone pollution over China's urban agglomerations. Heatwaves are becoming more common in urban clusters with serious ozone pollution. Studies have demonstrated that median surface ozone concentrations can surge significantly during periods of extreme heat, increasing ozone levels and exacerbating the problem of premature mortality due to ozone pollution (Tian et al. 2023), further complicating the environmental and public health landscape in China (Jacob and Winner 2009; Kerr et al. 2020; Lee et al. 2006). Domingo et al. (2024) assessed changes in short-term ozone-related excess deaths between 2050 and 2054 in 20 countries or regions and found that acute ozone-related excess deaths increased in all study scenarios except those consistent with the goals of the Paris Agreement.

This conjunction of heatwaves and ozone pollution represents a critical compound event that poses a multifaceted threat to health and wellbeing, particularly in densely populated urban areas (Ban et al. 2022; Ren et al. 2009; Yu et al. 2023). The Intergovernmental Panel on Climate Change (IPCC) has highlighted the significant role of human activity in escalating the risk of such extreme events since the mid-20th century (IPCC 2021). With global temperatures projected to rise, these compound events are expected to increase in both frequency and spatial extent, especially under scenarios predicting global warming of 2°C or more (Meehl et al. 2018; IPCC 2021). This increase is attributed to the synergistic effects of several meteorological conditions conducive to ozone formation—such as high temperatures, intense solar radiation, and stagnant air masses—that are likely to be amplified by ongoing climate change (Kou et al. 2023; Yang et al. 2022; Lee et al. 2015). Under a high-emission scenario (SSP3-7.0), the annual frequency of heatwave-ozone compound events across China is projected to increase by 34.6 days by 2071–2090 relative to the 1995–2014 baseline (Ban et al. 2022). Moreover, the intensification of these compound events is expected to exhibit substantial regional disparities, underscoring the importance of spatially explicit assessments of future climate-air pollution risks. Previous studies focusing on the city level have projected a significant uptick in the number of days experiencing both heatwaves and high ozone levels, underlining the potential for increased health risks associated with these compound events (Chen et al. 2024; Wang et al. 2023). Over time, the frequency of deaths and

the number of excess deaths due to these combined exposure events will show an upward trend (Du et al. 2024). One instance of this can be seen in the research findings that ozone and heatwave exposure had a significant synergistic effect on cardiovascular disease (CVD) mortality, with up to 5.8% of CVD deaths attributable to ozone and heatwaves. Generally, the higher the ozone exposure level, the higher the temperature threshold, and the longer the heatwave exposure (Du et al. 2024). Xu et al. (2024) also showed that exposure to both heatwaves and high ozone pollution events was associated with a higher risk of all-cause mortality compared to exposure to heatwave or high ozone pollution events alone. The annual average number of excess deaths due to concurrent events in China from 2017 to 2020 was 5.7 times higher than from 2013 to 2016. Using high-resolution (1 km) daily temperature and ozone data, Su et al. (2025) further quantified that urban population exposure to compound extreme heat and ozone pollution in Chinese cities increased by 67% from 2003 to 2020, with 38% of cities exhibiting significant upward trends, and core urban areas contributing over 80% to total exposure in major cities by 2020. Therefore, the combined effects of ozone and high temperature on human health deserve continuous attention as an environmental problem.

Urbanization has been shown to amplify the health risks associated with compound heatwave-ozone events through enhanced heat island effects and altered local atmospheric chemistry. For instance, Zong et al. (2022) quantified the synergistic health effects of heatwaves and ozone pollution in Beijing, reporting that favorable synoptic weather patterns and urbanization increased excess mortality from compound events by 33.09% and 18.95%, respectively. The interannual variability of summertime heatwave-ozone compound events is modulated not only by local meteorological conditions but also by large-scale climate patterns. Gao et al. (2023) identified that springtime sea surface temperature anomalies in the western Pacific Ocean, western Indian Ocean, and Ross Sea could offer preseasonal hints for predicting the co-occurrence of heatwaves and ozone pollution in China, achieving a correlation coefficient of 0.81 for the North China Plain.

As a vast and populous developing country, China's in-depth analysis of ozone pollution, heatwaves, and their compound events' spatiotemporal distribution across different regions is particularly crucial (Ban et al. 2022). Current research largely focuses on exploring the impact of ozone and heatwaves as individual factors on society and public health, with less comprehensive assessment of the spatiotemporal

dynamics of these factors' compound events and their population exposure (Chen et al. 2022a; Yan 2024). Despite epidemiological evidence suggesting that the health impacts of ozone pollution are exacerbated under the compounded conditions of high temperatures and elevated ozone levels, with some regions reporting significantly higher rates of excess mortality associated with these compound events compared to single occurrences (Hertig et al. 2020), there remain pronounced disparities in exposure and health risks across different regions (Ban et al. 2022). For example, urbanization leads to a higher risk of combined heatwaves and ozone events in urban areas than in rural areas (Zong et al. 2022). Recent studies have increasingly recognized the importance of compound extremes, including concurrent drought-heatwave events in northwestern China (Wang et al. 2026), yet the long-term evolution of heatwave-ozone compound events across multiple urban agglomerations remains less systematically characterized. Most studies have focused on ozone pollution trends since 2013, when the Chinese government implemented the Air Pollution Prevention and Control Action Plan, leaving the long-term evolution of ozone and its compound events over the past two decades less systematically characterized. The long-term spatiotemporal distribution of compound events and their coupling analysis with environmental and meteorological factors remains an area that requires further in-depth exploration.

Therefore, this study subdivides China into seven major regions to systematically investigate the spatiotemporal evolution of heatwaves, ozone pollution, and their compound events, as well as the underlying drivers of regional disparities, using refined gridded datasets. Specifically, the research quantifies how different heatwave types modulate ozone pollution risks and examines the shifting roles of meteorological, chemical, and socioeconomic factors in shaping ozone variability under climate warming. The specific objectives are threefold: (1) to characterize the spatiotemporal evolution of daytime, nighttime, and compound heatwaves, ozone pollution, and their compound events across China from 2000 to 2024; (2) to quantify the impacts of different heatwave types on ozone pollution risks across six major urban agglomerations using conditional probability and risk ratio metrics; and (3) to investigate how climate warming influences regional ozone formation mechanisms by examining changes in temperature sensitivity and the relative contributions of meteorological, chemical, and socioeconomic drivers between 2010 and 2020.

2. Data and methods

2.1 Data collection

2.1.1 Meteorological data

Daily maximum temperature (Tmax) and daily minimum temperature (Tmin) data from 1991 to 2024 were extracted from the CN05.1 dataset provided by the Climate Change Research Center (CCRC), Chinese Academy of Sciences (available at <https://ccrc.iap.ac.cn/resource/detail?id=228>) (Wu and Gao 2013; Wu et al. 2017; Xu et al. 2009), with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. Additional meteorological variables (wind speed, solar radiation, boundary layer height, etc.) were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis (Hersbach et al. 2020)..

2.1.2 Environmental data

Daily maximum 8-hour average (MDA8) ozone concentrations from 2000 to 2024 were derived from the CHAP dataset (available at <https://weijing-rs.github.io/product.html>), which has a sample-based cross-validation R^2 of 0.89 and RMSE of $15.77 \mu\text{g}/\text{m}^3$ (Wei et al. 2022; Yang et al. 2025). $\text{PM}_{2.5}$ and NO_2 data were also obtained from CHAP. All data were bilinearly interpolated to $0.25^{\circ} \times 0.25^{\circ}$ grids.

2.1.3 Socioeconomic data

Population density data were obtained from the LandScan dataset (~ 1 km resolution; available at <https://landscan.ornl.gov/>). GDP spatial distribution data were obtained from the Resource and Environmental Science Data Platform (available at <https://www.resdc.cn/DOI/DOI.aspx?DOIID=33>) (Xu 2017). Additionally, the normalized difference vegetation index (NDVI) was incorporated as a driving factor. NDVI data were derived from a daily gap-free dataset for China (1981-2023) developed by Li et al. (2024a), which was reconstructed from NOAA CDR daily NDVI data using spatiotemporal interpolation. The original 0.05° resolution data were aggregated to 0.25° grids via bilinear interpolation, and warm-season (April-September) averages from 2000 to 2023 were extracted for analysis.

2.2 Methods

2.2.1 Definition of heat, ozone, and concurrent extremes

Heatwave events were identified during the warm season (April-September) using a percentile-based threshold approach. Following previous studies, DHWs was defined as a period of at least two consecutive days during which $T_{\max}$ exceeded the 90th percentile threshold calculated from a 15-day moving window based on the 1991-2020 climatological reference period. NHWs was similarly defined using $T_{\min}$. CHWs were identified when both $T_{\max}$ and $T_{\min}$ simultaneously exceeded their respective thresholds for at least two consecutive days.

Ozone pollution events were characterized using the MDA8 O_3 . Following the Chinese Ambient Air Quality Standards (GB 3095-2012) and previous studies on long-term ozone variability in China (Lu et al. 2020), an ozone pollution day was defined when MDA8 O_3 exceeded $120 \mu\text{g}/\text{m}^3$, which represents a moderate pollution level between the Grade I ($100 \mu\text{g}/\text{m}^3$) and Grade II ($160 \mu\text{g}/\text{m}^3$) standards.

To investigate the interactions between heat extremes and ozone pollution, concurrent heatwave-ozone events were defined as days when ozone pollution occurred during a heatwave period. Three categories of compound events were considered according to heatwave type, including daytime heatwave-ozone events (DHW- O_3), nighttime heatwave-ozone events (NHW- O_3), and compound heatwave-ozone events (CHW- O_3).

In addition to event occurrence, this study further quantified the probability of ozone pollution under different heatwave conditions using conditional probability analysis. This framework allows the assessment of how daytime, nighttime, and compound heatwaves modify ozone pollution risks across different regions and urban agglomerations in China.

2.2.2 Urban agglomeration division

To further investigate regional differences in ozone responses to heatwaves and the spatial heterogeneity of ozone-driving mechanisms, six major urban agglomerations were selected for detailed analysis (Fig. 1). These urban agglomerations include the Beijing-Tianjin-Hebei (BTH), Central China (CEN), Eastern China (EST), Northeast China Plain (NEP), Pearl River Delta (PRD), and Sichuan Basin (SCB) regions.

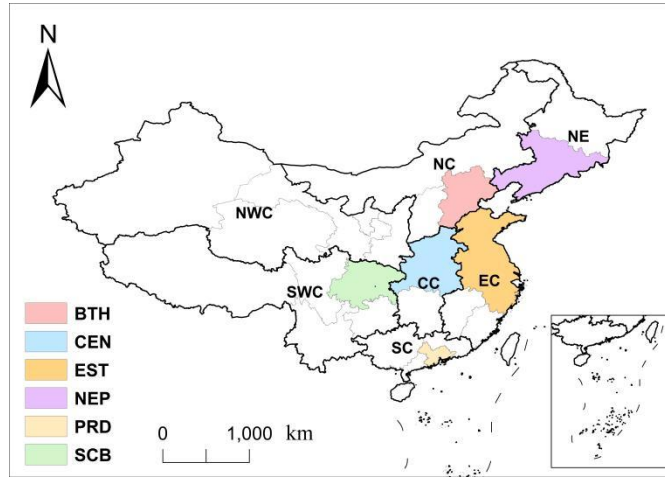


Fig. 1. Spatial distribution of the seven geographical divisions (black boundaries) and the six urban agglomerations (colored areas) selected for regional analysis in this study. The six urban agglomerations include: Beijing-Tianjin-Hebei (BTH, red), Central China (CEN, blue), Eastern China (EST, orange), Northeast China Plain (NEP, purple), Pearl River Delta (PRD, yellow), and Sichuan Basin (SCB, green). The seven divisions outlined in black correspond to Northwest China (NWC), North China (NC), Northeast China (NE), East China (EC), Central China (CC), South China (SC), and Southwest China (SWC), which are used for regional aggregation in the spatiotemporal trend analyses presented in subsequent sections.

These urban agglomerations represent the most densely populated and economically developed regions in China and account for a substantial proportion of the country's industrial activities, energy consumption, and anthropogenic emissions. At the same time, they exhibit pronounced differences in climatic conditions, topographic characteristics, and ozone pollution levels. For example, BTH and EST are located in highly urbanized plains with intensive industrial and transportation emissions, whereas SCB is characterized by basin topography that favors pollutant accumulation. NEP experiences relatively cool climatic conditions and weaker photochemical activity, while PRD is strongly influenced by maritime circulation.

The selected urban agglomerations cover the major ozone-pollution hotspots identified in previous studies and provide representative examples of different ozone formation environments across China. Therefore, they offer an appropriate framework for examining regional variations in heatwave-ozone interactions and for exploring the spatially heterogeneous effects of meteorological and anthropogenic drivers using the MGWR model.

2.2.3 Conditional Probability

To quantify the heatwave impact on O₃ pollution, we calculated the unconditional probability P(O₃) and conditional probability P(O₃|HW):

$$P(O_3|HW) = \frac{N(O_3 \cap HW)}{N(HW)} \quad (1)$$

where $N(O_3 \cap HW)$ denotes the number of days during which ozone pollution and heatwave events occurred simultaneously, and $N(HW)$ represents the total number of heatwave days.

The risk ratio (RR) was then derived as:

$$RR = \frac{P(O_3|HW)}{P(O_3)} \quad (2)$$

where $P(O_3)$ is the unconditional probability of ozone pollution. An $RR > 1$ indicates an elevated O₃ risk during heatwaves. We calculated RR for DHWs, NHWs, and CHWs across six major urban agglomerations.

2.2.4 Spatial Autocorrelation Analysis

Before conducting the MGWR analysis, the spatial autocorrelation of ozone pollution was evaluated using Global Moran's I statistic. Spatial autocorrelation measures the degree to which neighboring locations exhibit similar values and is widely used to identify spatial clustering patterns in environmental variables.

Global Moran's I is calculated as:

$$I = \frac{n}{\sum_{i=1}^n \sum_{j=1}^n \omega_{ij}} \cdot \frac{\sum_{i=1}^n \sum_{j=1}^n \omega_{ij} (z_i - \bar{z})(z_j - \bar{z})}{\sum_{i=1}^n (z_i - \bar{z})^2} \quad (3)$$

where n is the total number of spatial units, z_i and z_j represent the ozone concentration values at locations i and j , respectively, $\bar{z}$ is the mean ozone concentration, ω_{ij} denotes the spatial weight between locations i and j .

The value of Moran's I ranges from -1 to 1. Positive values indicate spatial clustering of similar ozone concentrations, negative values indicate spatial dispersion, and values close to zero suggest a random spatial distribution. Statistical significance was assessed using Z-scores and corresponding p-values.

Local indicators of spatial association (LISA) are employed to detect local cluster types for each grid cell in relation to its neighborhood, thereby addressing the limitation of global measures that cannot locate cluster positions. The local Moran's I_i statistic is computed for each cell i :

$$I_i = \frac{(z_i - \bar{z})}{\frac{1}{n} \sum_{i=1}^n (z_i - \bar{z})^2} \sum_j \omega_{ij} (z_j - \bar{z}) \quad (4)$$

Based on the local Moran's I statistic, spatial patterns were classified into four

categories: high-high (HH), low-low (LL), high-low (HL), and low-high (LH). These categories represent hotspots, cold spots, and spatial outliers of ozone pollution.

The spatial autocorrelation analysis provides a basis for evaluating the spatial dependence of ozone pollution and supports the application of MGWR to investigate spatially varying relationships between ozone concentrations and their driving factors.

2.2.5 MGWR

Unlike traditional GWR, MGWR allows each independent variable to have its own optimal bandwidth, capturing spatially heterogeneous relationships at different scales. We used MGWR to model O₃ concentration as a function of meteorological (Tmax, solar radiation, relative humidity, wind speed), chemical (PM_{2.5}, NO₂), and socioeconomic (population density, GDP) drivers for the years 2010 and 2020. The model is specified as follows:

$$y_i = \sum_{j=1}^k \beta_{ij} \omega_j(u_i, v_i) x_{ij} + \varepsilon_i \quad (5)$$

where ω_j denotes the variable-specific bandwidth for the j -th explanatory variable, and β_{ij} represents the local regression coefficient for the j -th variable at location i .

3. Results

3.1 Spatiotemporal trends of heatwaves

Based on meteorological observation data from 2000 to 2024, this study presents a statistical analysis of heatwave events in China, including DHWs, NHWs, and CHWs. The corresponding spatiotemporal distributions are illustrated in Figure 2.

Between 2000 and 2024, all heatwave types exhibited significant upward trends across China, although their spatial distributions and growth rates differed substantially. DHWs occurred most frequently in North China, the Huang-Huai region, and the middle-lower reaches of the Yangtze River, whereas NHWs affected a broader spatial extent, particularly in South China and the Yangtze River Basin. CHWs were concentrated mainly in southern China and displayed a distinct south-north gradient.

Temporal analysis revealed that NHWs increased more rapidly than DHWs, especially after 2015, while CHWs exhibited the fastest growth rate among all heatwave categories. This finding suggests that climate warming in China is

increasingly characterized by persistent day-night heat stress rather than isolated daytime extreme heat events. The accelerated increase in CHWs indicates a growing likelihood of prolonged thermal exposure and associated environmental risks.

Regional differences were also evident. Heatwave increases were particularly pronounced in Southwest and Northeast China, whereas North China and Eastern China maintained high heatwave frequencies throughout the study period. These patterns imply that climate warming is expanding heatwave impacts beyond traditionally vulnerable regions.

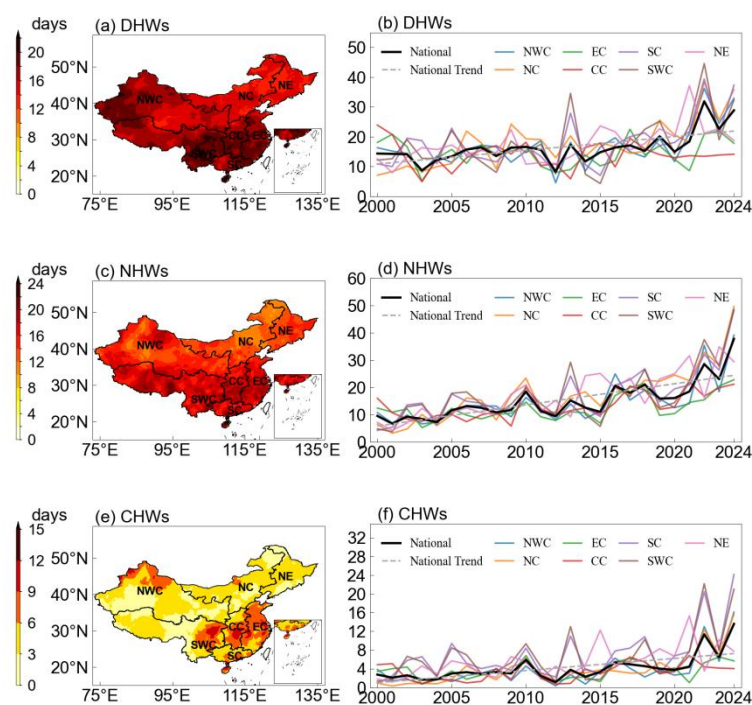


Figure 2. Spatial distribution and temporal evolution of DHWs, NHWs, and CHWs over China and different regions during 2000-2024.

(a) DHWs; (b) interannual variations of DHWs by region; (c) NHWs; (d) interannual variations of NHWs by region; (e) CHWs; and (f) interannual variations of CHWs by region. The solid black line indicates the national mean, while the dashed line indicates the linear trend.

3.2 Spatial patterns and temporal evolution of ozone pollution

Based on multiple thresholds (O_3_{100} , O_3_{120} , and O_3_{160}), the spatiotemporal distribution and variation characteristics of ozone pollution days in China are illustrated in Figure 3.

Ozone pollution exhibited a pronounced spatial gradient, with consistently higher frequencies in eastern China than in western China. High-value areas were

concentrated in the North China Plain, the Yangtze River Delta, and several densely populated urban agglomerations, indicating the combined influence of favorable photochemical conditions and intensive anthropogenic emissions.

Although ozone pollution increased nationwide during 2000-2024, the increase was not uniform across pollution levels. Moderate ozone pollution events ($\text{MDA8 O}_3 > 100 \mu\text{g/m}^3$) increased most rapidly, suggesting a widespread deterioration of regional ozone exposure. Meanwhile, severe pollution events also showed an increasing trend, indicating that high-intensity ozone episodes remain an emerging environmental concern.

The increase in ozone pollution accelerated after approximately 2015, coinciding with the rapid growth of extreme heat events. This temporal consistency suggests an increasingly important role of climate conditions in shaping ozone variability across China.

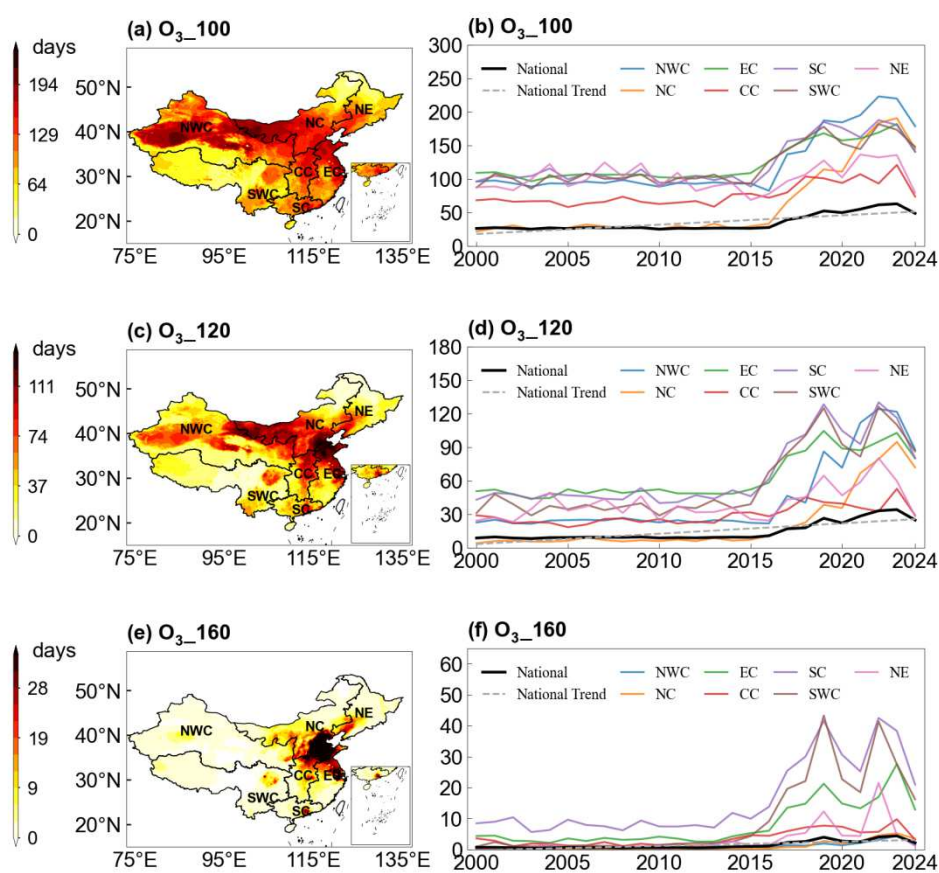


Figure 3. Spatial distribution and temporal variations of ozone pollution days under different ozone concentration thresholds across China during 2000-2024.

(a-b) O_3_100 (MDA8 $O_3 \geq 100 \mu g/m^3$); (c-d) O_3_120 (MDA8 $O_3 \geq 120 \mu g/m^3$); and (e-f) O_3_160 (MDA8 $O_3 \geq 160 \mu g/m^3$), showing their spatial distributions and interannual variations, respectively. The solid black line represents the national average, and the dashed line represents the linear trend.

Regional divisions are identical to those in Figure 2.

3.3 Expansion of heatwave-ozone compound events

Based on the identification of compound extreme events defined by the concurrent occurrence of heatwaves and ozone pollution, their spatiotemporal distribution characteristics are illustrated in Figure 4.

Heatwave-ozone compound events showed stronger spatial concentration than either heatwaves or ozone pollution alone. The highest frequencies occurred in the North China Plain, the Yangtze River Delta, and coastal South China, where intensive precursor emissions coincide with favorable meteorological conditions for ozone formation.

The occurrence frequent of compound events remained relatively stable before 2015 but increased rapidly afterward, with the strongest growth observed after 2020. This increase exceeded the growth rates of individual heatwave and ozone events, indicating a nonlinear amplification of compound climate-air pollution risks under ongoing warming.

Notably, regions experiencing rapid increases extended beyond traditional hotspots. Southwest China and Eastern China exhibited the strongest growth, while Northeast China, despite relatively low historical frequencies, showed a clear emerging trend. These results suggest that compound heatwave-ozone hazards are becoming geographically more widespread and increasingly important for regional risk management.

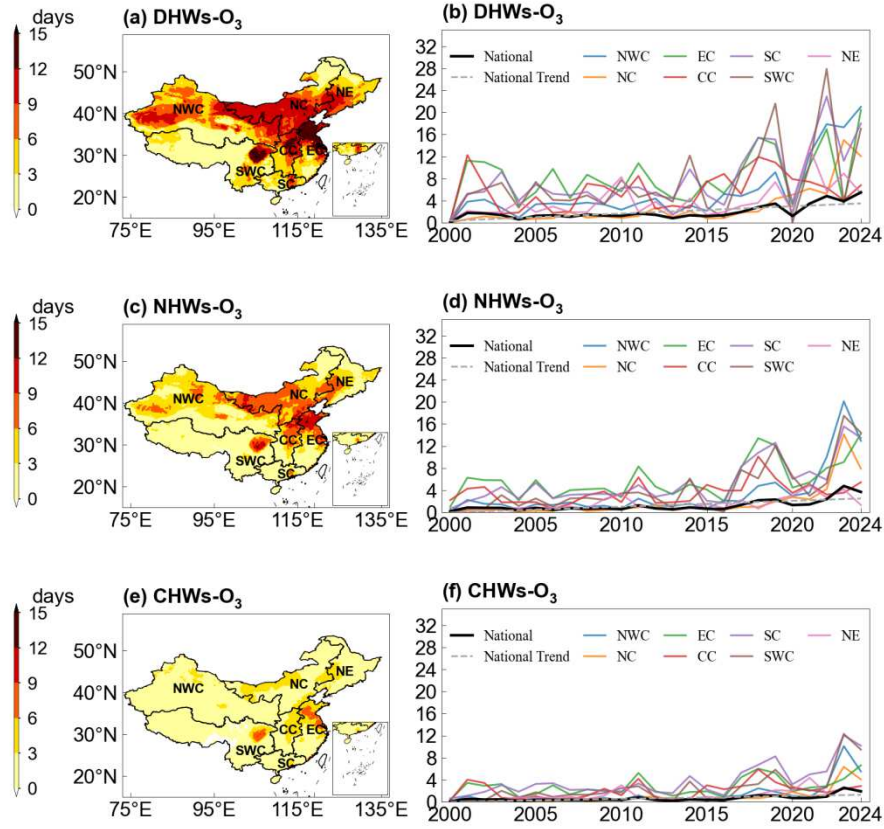


Figure 4. Spatial distribution and temporal evolution of DHW-O₃, NHW-O₃, and CHW-O₃ compound events across China during 2000-2024.

(a-b) DHW-O₃ compound events; (c-d) NHW-O₃ compound events; and (e-f) CHW-O₃ compound events, showing their spatial distributions and interannual variations, respectively. The solid black line indicates the national mean, while the dashed line indicates the linear trend. Regional divisions are the same as those shown in Figure 2.

3.4 Conditional probability of ozone pollution under different heatwave types

Figure 5 presents the spatial distribution of ozone pollution conditional probabilities under different heatwave conditions, while Table 1 summarizes the corresponding risk ratio (RR) for six major urban agglomerations.

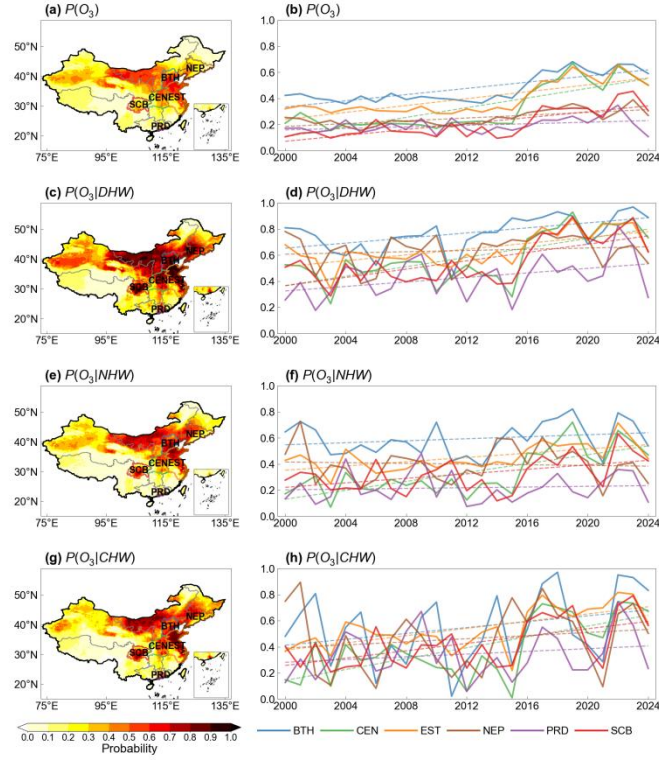


Figure 5. Spatial patterns and interannual variations of ozone pollution probabilities under different heatwave conditions across China during 2000-2024.

(a-b) Baseline ozone pollution probability [$P(O_3)$]; (c-d) conditional probability of ozone pollution occurrence during daytime heatwaves [$P(O_3|DHW)$]; (e-f) conditional probability of ozone pollution occurrence during nighttime heatwaves [$P(O_3|NHW)$]; and (g-h) conditional probability of ozone pollution occurrence during compound heatwaves [$P(O_3|CHW)$]. The left panels show spatial distributions, and the right panels show annual variations for the six major urban agglomerations.

Table 1 Mean risk ratio (RR) of ozone pollution under different heatwave types across six major urban agglomerations during 2000-2024.

regions	DHW-RR	NHW-RR	CHW-RR
BTH	1.65	1.27	1.14
CEN	1.94	1.04	1.20
EST	1.68	1.17	1.38
NEP	2.60	1.62	1.80
PRD	2.24	1.11	1.77
SCB	2.99	1.71	2.22

Overall, heatwaves substantially increased the probability of ozone pollution across China. Under non-heatwave conditions, ozone pollution was mainly concentrated in the NEP the EST, and several densely populated urban regions. When heatwaves occurred, ozone pollution probabilities increased markedly and expanded to a broader geographical extent. The enhancement effect was most pronounced under DHWs, followed by CHWs, whereas NHWs generally exhibited weaker impacts.

At the national scale, the mean conditional probability of ozone pollution increased from 0.071 under normal conditions to 0.125 during DHWs, 0.091 during CHWs, and 0.082 during NHWs. This pattern indicates that daytime thermal and radiative conditions play the dominant role in promoting photochemical ozone formation. Strong solar radiation during DHWs accelerates photochemical reactions involving NO_x and VOCs, leading to more efficient ozone production. In contrast, NHWs occur under limited radiation conditions, reducing the efficient of ozone generation despite elevated temperatures.

Substantial regional heterogeneity was observed among the six urban agglomerations. BTH consistently exhibited the highest conditional ozone probabilities under all heatwave categories, with mean probabilities reaching 0.770 during DHWs, 0.594 during NHWs, and 0.548 during CHWs. These high values reflect the elevated background ozone pollution levels associated with intensive industrial activities, dense transportation networks, and large precursor emissions in the region.

However, RR analysis revealed a different pattern. The strongest heatwave-induced enhancement of ozone pollution occurred in the SCB, where the mean RR reached 2.99 during DHWs, 1.71 during NHWs, and 2.22 during CHWs. Northeast China lain (NEP) also showed high sensitivity, with corresponding RR values of 2.60, 1.62, and 1.80. These results indicate that ozone pollution in SCB and NC responds more strongly to heatwave conditions despite their lower background ozone probabilities. The exceptionally high RR values in SCB likely reflect the combined influence of basin topography, weak ventilation, and stagnant meteorological conditions, which facilitate pollutant accumulation during extreme heat events.

Among the three heatwave categories, DHWs consistently generated the highest RR values in all urban agglomerations. The average RR exceeded 1.5 in every region and reached nearly 3.0 in SCB. By comparison, NHWs exerted considerably weaker

influences. In several regions, including CEN and the PRD, NHW-RR values were close to or even below unity in some years, indicating that nighttime warming alone does not necessarily increase ozone pollution risk. This finding highlights the critical role of solar radiation in ozone photochemistry.

CHWs exhibited intermediate but persistent impacts. Although their RR values were generally lower than those associated with DHWs, CHWs often produced higher conditional probabilities because they combined enhanced daytime photochemistry with sustained nighttime warming. EST and CC showed particularly pronounced increases in ozone probability during CHWs, suggesting that prolonged thermal stress may increasingly contribute to future compound climate-air pollution extremes.

Temporal analysis further showed that RR values generally declined during 2000-2024 despite increasing ozone probabilities. Significant downward trends were observed for DHW-RR in BTH, CEN, EC, NC, and SCB, while NHW-RR also decreased in most regions. This pattern suggests that although ozone pollution has become more frequent under climate warming, the relative enhancement associated with individual heatwave events has weakened. A likely explanation is that rising background ozone levels, together with changes in precursor emissions and atmospheric chemical regimes, have partially reduced the relative contribution of heatwave events to ozone pollution occurrence.

Overall, the results demonstrate that heatwaves substantially elevate ozone pollution risk across China, but the magnitude of enhancement varies considerably among regions and heatwave types. DHWs exert the strongest influence on ozone occurrence, whereas compound heatwaves contribute to sustained high-risk conditions through prolonged day-night thermal stress. The contrasting patterns between conditional probability and RR further indicate that regions with the highest background ozone pollution are not necessarily the most sensitive to heatwave forcing. Instead, heatwave-induced ozone amplification is particularly pronounced in regions such as SCB and NC, where climatic conditions exert stronger control on ozone formation.

3.5 Driving factors of ozone pollution from MGWR

3.5.1 Spatial autocorrelation

To investigate the spatial dependence of ozone pollution, Global Moran's I and LISA analyses were conducted for six major urban agglomerations. The results

revealed significant positive spatial autocorrelation of O₃ concentrations in all regions during both 2010 and 2020 (Table 2), indicating that neighboring cities tended to exhibit similar ozone pollution levels.

Table 2. Global Moran's I statistics of ozone concentrations in six major urban agglomerations in 2010 and 2020.

regions	year	Global moran's I	Significance
BTH	2010	0.286	0.001
	2020	0.292	0.001
CEN	2010	0.900	0.001
	2020	0.522	0.001
EST	2010	0.447	0.001
	2020	0.280	0.001
NC	2010	0.267	0.001
	2020	0.387	0.001
PRD	2010	0.173	0.006
	2020	0.237	0.001
SCB	2010	0.753	0.001
	2020	0.843	0.001

Strong spatial autocorrelation of ozone concentrations was observed in all six urban agglomerations in both 2010 and 2020 (Table 2). However, the magnitude of spatial clustering and its temporal changes varied considerably among regions. The most pronounced change occurred in CEN, where Moran's I declined markedly from 0.900 in 2010 to 0.522 in 2020, indicating a substantial weakening of spatial aggregation despite persistently significant clustering ($p < 0.001$). EST also experienced a notable decrease, with Moran's I falling from 0.447 to 0.280 over the same period.

In contrast, SCB exhibited a moderate increase in spatial autocorrelation, with Moran's I rising from 0.753 to 0.843. NEP and PRD showed relatively small increases,

from 0.267 to 0.387 and from 0.173 to 0.237, respectively, suggesting gradually strengthening regional aggregation. BTH maintained relatively stable spatial autocorrelation throughout the study period, with Moran's I increasing only slightly from 0.286 to 0.292.

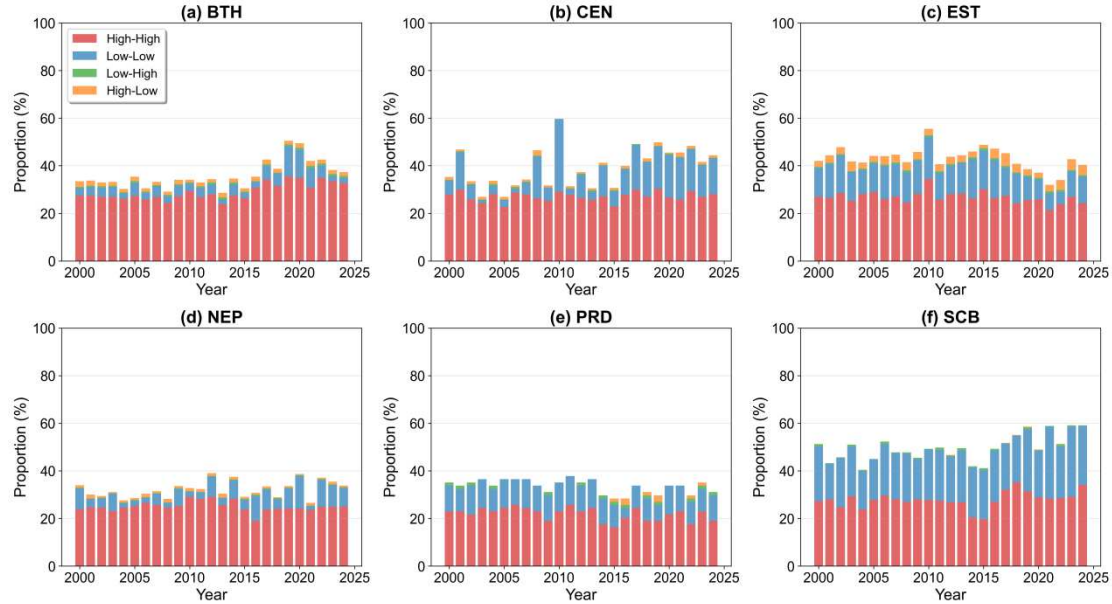


Figure 6. Temporal evolution of local spatial clustering patterns of ozone concentrations in six major urban agglomerations during 2000-2024

The LISA results further revealed distinct spatial clustering patterns among the six urban agglomerations. HH clusters and LL clusters were the dominant local spatial association types, whereas HL and LH outliers occurred only sporadically. In BTH, HH clusters were mainly concentrated in the southern and central plains, while LL clusters occurred primarily in the northern mountainous areas. The spatial extent of HH clusters expanded slightly between 2010 and 2020, indicating enhanced regional connectivity of ozone pollution. In CEN, HH clusters remained concentrated in the northern part of the region around the Zhengzhou metropolitan area, whereas LL clusters were primarily distributed in southwestern mountainous areas. EST exhibited the largest contiguous HH cluster zone among all urban agglomerations, extending across southern Shandong and northern Jiangsu. Meanwhile, LL clusters were concentrated in southern Zhejiang, forming a pronounced north-south spatial contrast.

Distinct clustering characteristics were also observed in NEP, PRD, and SCB. In NEP, HH clusters were mainly located in the central Liaoning urban belt, while LL clusters expanded in eastern Jilin and Heilongjiang by 2020, indicating increasing spatial differentiation. PRD showed relatively weak local spatial clustering, with only

limited HH clusters distributed around the Guangzhou-Foshan metropolitan core. In SCB, HH clusters were concentrated in the central basin area, whereas LL clusters were distributed near the western and eastern margins of the basin. The expansion and consolidation of HH clusters between 2010 and 2020 suggest strengthened spatial aggregation of ozone pollution within the SCB.

Temporal changes in cluster composition further supported these findings (Figure 6). HH clusters accounted for the largest proportion in most urban agglomerations and generally increased after 2015, particularly in BTH and SCB. The proportion of LL clusters also remained relatively high in several regions, indicating persistent spatial polarization between high- and low-pollution areas. In contrast, HL and LH clusters consistently occupied only a small fraction of the total area, suggesting that transitional or anomalous spatial associations were relatively limited. Overall, the results demonstrate that ozone pollution exhibits pronounced spatial clustering across China's major urban agglomerations, with regional aggregation becoming increasingly evident in several key regions during recent years.

3.5.2 Tmax sensitivity on O₃ concentrations

The MGWR-derived local regression coefficients for Tmax, representing the change in MDA8 O₃ concentration (in $\mu\text{g}/\text{m}^3$) associated with a 1°C increase in daily maximum temperature, were used as a metric of temperature sensitivity. Positive coefficients indicate warming-induced ozone enhancement, whereas larger values denote stronger climatic control over regional ozone formation.

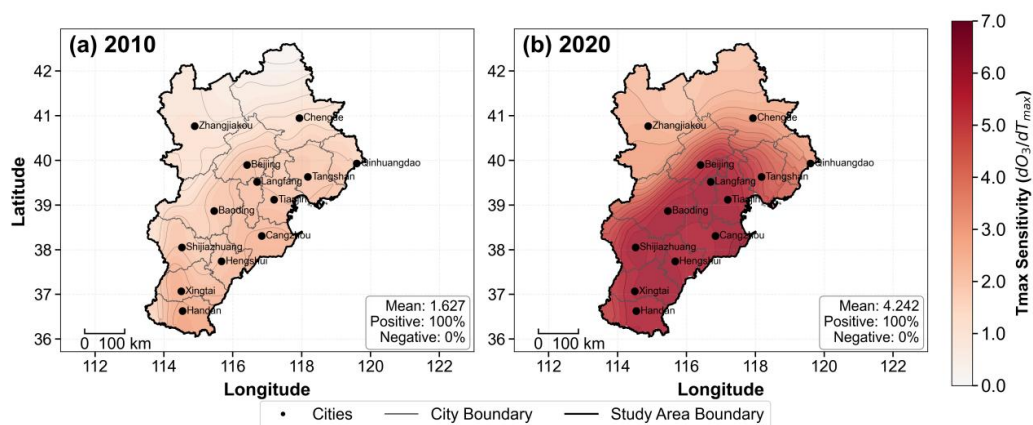


Figure 7. Spatial distribution of Tmax sensitivity coefficients (in $\mu\text{g}/\text{m}^3$ per °C) for MDA8 O₃ concentrations in the BTH region in 2010 and 2020.

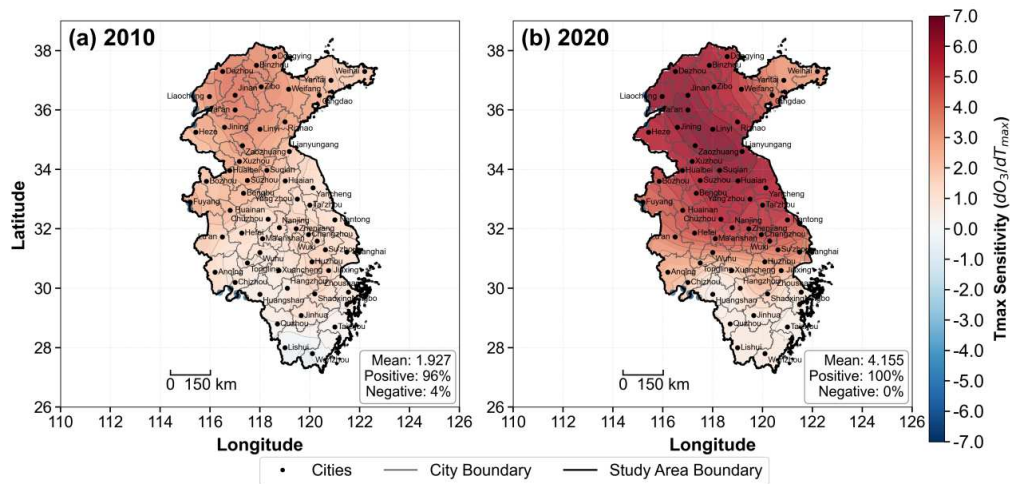


Figure 8. Spatial distribution of Tmax sensitivity coefficients (in $\mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$) for MDA8 O_3 concentrations in the EST region in 2010 and 2020.

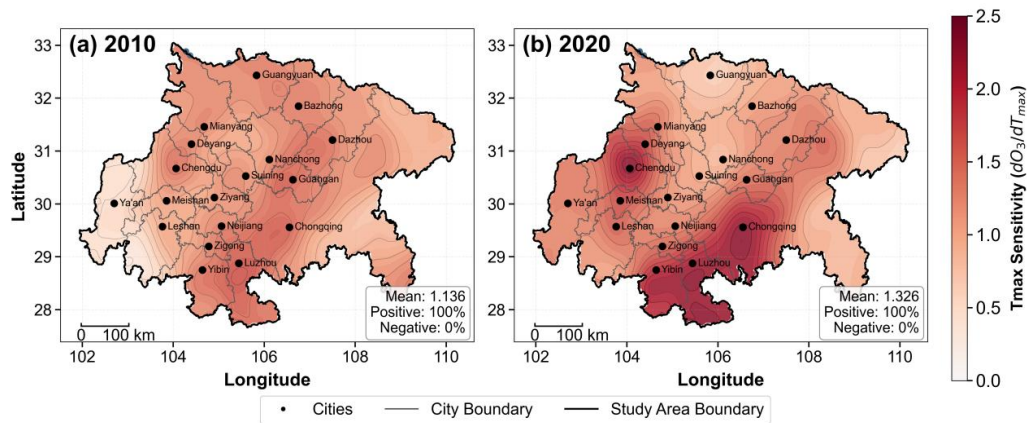


Figure 9. Spatial distribution of Tmax sensitivity coefficients (in $\mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$) for MDA8 O_3 concentrations in the SCB region in 2010 and 2020.

Substantial increases in Tmax sensitivity were observed in BTH, EST, and CEN between 2010 and 2020. In BTH, the regional mean sensitivity increased from 1.63 to $4.24 \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$, with high-sensitivity zones expanding from southern Hebei to encompass most of the central and southern plains; particularly strong responses (exceeding $5.0 \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$ by 2020) were observed in Shijiazhuang, Xingtai, and Handan. Similarly, EST showed a marked increase from 1.93 to $4.16 \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$, with high-sensitivity regions expanding across northern Jiangsu, northern Anhui, and Shandong Province to form a continuous belt of strong temperature dependence. CEN also experienced a substantial rise from 2.59 to $3.60 \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$, with the enhancement most pronounced in northern Henan, while western Hubei remained characterized by relatively weak temperature effects.

In contrast, PRD and SCB exhibited only modest increases: from 1.52 to 1.65

$\mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$ in PRD, with enhanced sensitivities concentrated around Guangzhou-Foshan; and from 1.14 to 1.33 $\mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$ in SCB, where persistent high-sensitivity zones remained concentrated in southern Sichuan and the Chongqing metropolitan area. A contrasting pattern was observed in NEP, where the regional mean sensitivity declined from 1.23 to 0.84 $\mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$, with areas of weak temperature sensitivity expanding across Jilin and eastern Liaoning. Overall, the influence of warming on ozone formation intensified substantially in BTH, EST, and CEN, whereas changes were modest in PRD and SCB and declined in NEP, highlighting pronounced regional heterogeneity in ozone sensitivity to climate warming across China.

3.5.3 Relative contributions of different drivers

(1) Beijing-Tianjin-Hebei (BTH) region

The BTH region exhibited a pronounced enhancement in meteorological control on ozone formation between 2010 and 2020. In 2010, ozone variability was jointly regulated by temperature, solar radiation, and precursor-related factors. By 2020, T_{max} became the dominant positive driver, accompanied by a substantial increase in its standardized coefficient and spatial significance.

Solar radiation (SSRD) also maintained a strong positive contribution, indicating that enhanced photochemical activity under warmer and sunnier conditions increasingly promoted ozone production. Relative humidity (RH) consistently exerted a negative influence, reflecting the suppression of ozone accumulation under moist atmospheric conditions.

Although NO_2 and $\text{PM}_{2.5}$ remained important contributors, their relative importance weakened over time. This pattern suggests a gradual transition toward a climate-sensitive ozone formation regime, in which meteorological conditions increasingly regulate ozone variability under the existing emission background.

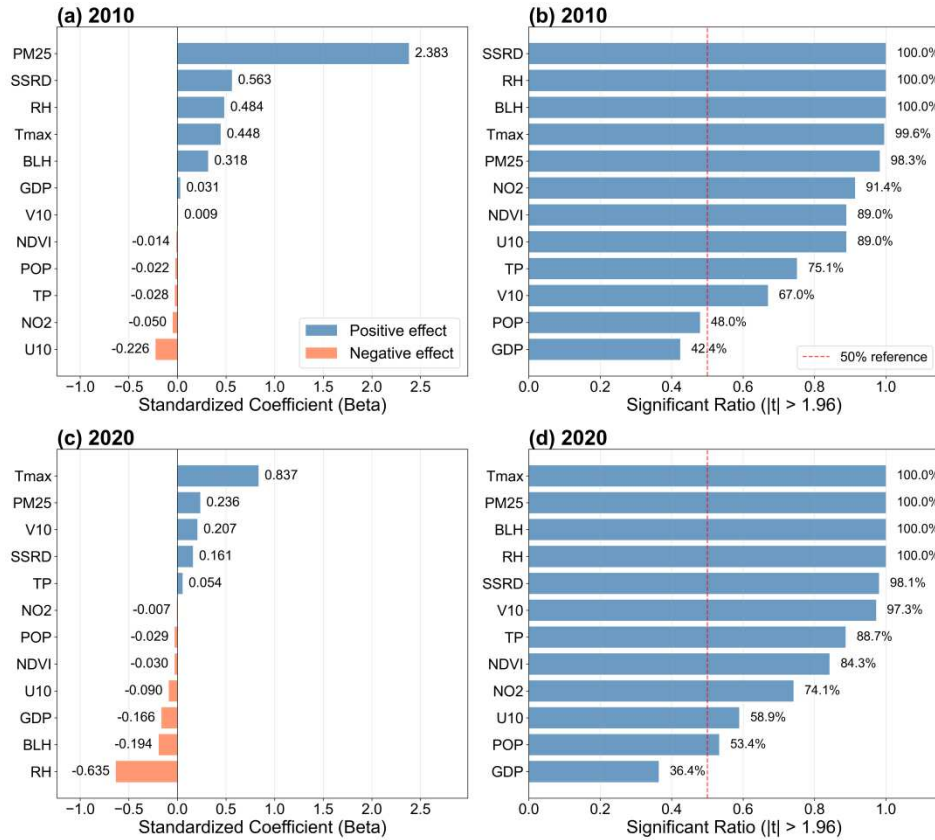


Figure 10. Relative contributions of different driving factors to ozone concentrations in BTH region based on the MGWR model.

(2) Eastern China Urban Agglomeration (EST)

The EST region showed the strongest increase in temperature sensitivity among all regions. In 2010, ozone formation was influenced by both meteorological and anthropogenic factors, with relatively balanced contributions from Tmax, SSRD, NO₂, and PM_{2.5}.

By 2020, Tmax became overwhelmingly dominant, and its standardized coefficient increased substantially. Solar radiation also remained an important positive driver, while RH became the primary inhibiting factor.

The reduced importance of precursor-related variables suggests that ozone variability in EST region is increasingly controlled by atmospheric conditions. Given the region's high population density and rapid urbanization, this enhanced climatic sensitivity may substantially increase future ozone exposure risks under warming scenarios.

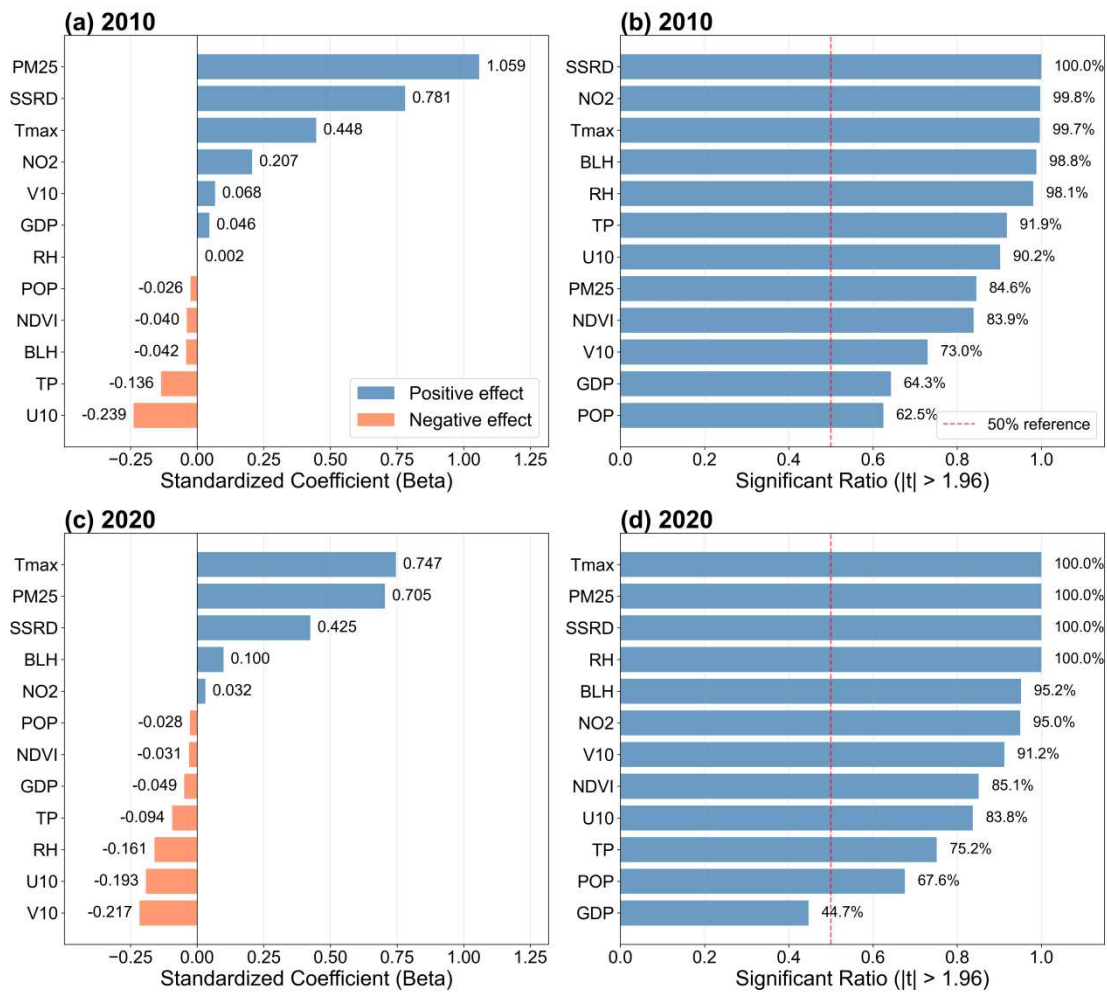


Figure 11. Relative contributions of different driving factors to ozone concentrations in EST region based on the MGWR model.

(3) Sichuan Basin (SCB) region

The SCB region remained strongly constrained by meteorological conditions throughout the study period. Tmax consistently represented the most influential positive driver, while RH exerted a persistent negative effect.

The basin topography of the region favors pollutant accumulation and enhances the sensitivity of ozone formation to temperature changes. As a result, the relative contribution of Tmax increased further between 2010 and 2020.

In contrast, precursor-related variables exhibited comparatively limited influence, indicating that regional ozone variability is primarily regulated by climatic factors rather than emission fluctuations. The increasing temperature sensitivity observed across the basin highlights the potential for intensified ozone pollution under future warming conditions.

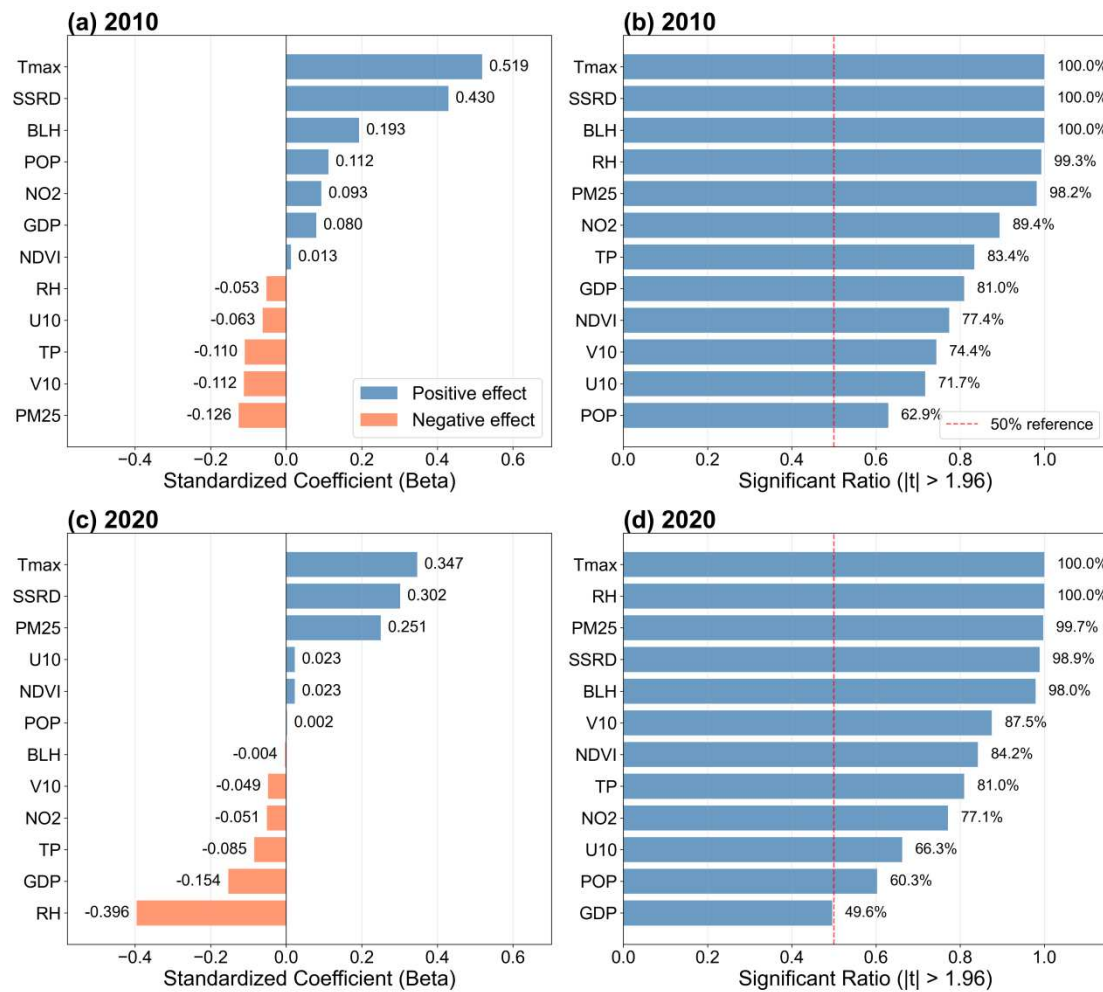


Figure 12. Relative contributions of different driving factors to ozone concentrations in SCB based on the MGWR model.

Overall, substantial regional differences were identified in the relative contributions of ozone drivers. BTH region, CEN region, and EST region exhibited the most evident enhancement of temperature control between 2010 and 2020, indicating an increasing shift toward meteorology-dominated ozone formation regimes. In contrast, NEP region and SCB remained primarily constrained by climatic factors throughout the study period, whereas the PRD region continued to exhibit strong influences from both meteorological conditions and anthropogenic emissions. These findings suggest that climate warming is progressively strengthening the role of meteorological drivers in shaping regional ozone variability across China, although the magnitude of this transition varies considerably among urban agglomerations.

4. Discussion

4.1 Climate warming is accelerating compound heatwave-ozone risks across

China

This study revealed significant increases in heatwaves, ozone pollution, and heatwave-ozone compound events across China during 2000-2024. The growth rate of compound events exceeded that of either hazard alone, suggesting that climate warming amplifies environmental risks through the interaction of multiple extremes rather than through isolated changes in temperature or air quality. Among the three heatwave categories, NHWs and CHWs exhibited the most rapid increases, consistent with growing evidence that nighttime warming is occurring faster than daytime warming in many regions (Zong et al. 2022). Elevated nighttime temperatures reduce surface cooling and increase atmospheric stability, thereby extending the duration of heat stress and limiting pollutant dispersion. The rapid expansion of compound events after 2015 indicates that the interaction between climate extremes and air pollution is becoming increasingly important, with disproportionate impacts on public health, ecosystems, and urban sustainability.

4.2 Differential ozone responses to daytime, nighttime, and compound heatwaves

Different heatwave types exert markedly different influences on ozone pollution. DHWs produced the largest increase in ozone pollution probability across most urban agglomerations, whereas NHWs generally exhibited weaker effects. This difference reflects the fundamental photochemical mechanisms of ozone formation: elevated temperatures accelerate reaction rates between NO_x and VOCs, while strong solar radiation enhances photolysis processes that drive ozone production. Therefore, DHWs simultaneously strengthen both thermal and radiative controls on ozone formation. In contrast, NHWs occur under conditions of limited solar radiation; although higher nighttime temperatures can influence atmospheric stability and pollutant carryover, photochemical ozone production remains relatively weak. CHWs represent a distinct category because they combine enhanced daytime photochemistry with persistent nighttime warming, substantially increasing cumulative ozone exposure and contributing to prolonged high-ozone episodes. Observational evidence from Beijing further confirms that CHWs significantly amplify diurnal ozone fluctuations accompanied by the accumulation of reactive nitrogen species (NO_x , NO_z , and NO_y), accelerating photochemical ozone production and promoting VOC-driven chain reactions (Wang et al. 2025). The RR analysis indicates that DHWs generally produced the highest RR, particularly in the SCB and NC, highlighting the strong sensitivity of ozone formation to daytime thermal conditions.

4.3 Regional heterogeneity reflects different ozone formation regimes

The responses of ozone pollution to heatwaves varied considerably among China's major urban agglomerations. BTH exhibited the highest conditional ozone probabilities, whereas the SCB showed the strongest relative enhancement under heatwave conditions. These contrasting responses suggest substantial regional differences in ozone formation regimes. The BTH region is characterized by intensive industrial activities, dense transportation networks, and historically high precursor emissions, resulting in relatively high background pollution probabilities. In contrast, the SCB is strongly influenced by topographic characteristics-weak ventilation, frequent stagnant conditions, and complex terrain favor pollutant accumulation, producing disproportionately large increases in ozone pollution risk under heatwave conditions. The increasing $T_{\max}$ sensitivity identified in BTH, CEN, and EST further suggests that climate warming is strengthening the climatic regulation of ozone formation in highly urbanized regions. Using a coupled meteorology-chemistry model, Li et al. (2024b) demonstrated that the record-breaking heatwaves in 2013 and 2022 accelerated photochemical ozone production by boosting both anthropogenic and biogenic emissions, while simultaneously suppressing dry deposition due to water-stressed vegetation, leading to more than a 30% increase in ozone pollution over China's urban agglomerations. Their findings further highlight that future high-emission scenarios, such as SSP370 and SSP585, are projected to intensify the co-occurrence of heatwaves and ozone extremes.

4.4 Climate warming is strengthening the climatic sensitivity of ozone pollution

The MGWR results further revealed divergent trajectories in ozone formation regimes across the six urban agglomerations between 2010 and 2020. The most pronounced shift toward meteorological dominance occurred in BTH, CEN, and EST, where $T_{\max}$ sensitivity more than doubled or increased substantially, and the relative importance of precursor-related variables (NO_2 and $\text{PM}_{2.5}$) declined concurrently. In these regions, ozone formation evolved from a mixed-control regime toward one increasingly governed by temperature and solar radiation, implying that future warming may progressively override emission reductions in regulating ozone variability.

In contrast, SCB remained strongly temperature-sensitive throughout the study period, with consistently high $T_{\max}$ sensitivity ($1.14\text{--}1.33\ \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$) and persistently dominant meteorological control. This stable but elevated sensitivity

likely reflects the region's basin topography, which favors pollutant accumulation and enhances the climatic response of ozone formation (Wang et al. 2025). PRD also exhibited relatively modest changes in sensitivity ($1.52 \rightarrow 1.65 \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$), with precursor-related factors retaining a comparatively stronger influence than in other regions, suggesting a continued role of anthropogenic emissions in modulating local ozone levels.

NEP exhibited a unique declining trend in T_{max} sensitivity ($1.23 \rightarrow 0.84 \mu\text{g}/\text{m}^3$ per $^{\circ}\text{C}$), possibly due to its relatively cooler background climate, where photochemical activity remains less temperature-limited compared with the warmer southern and central regions. This pattern indicates that the influence of climate warming on ozone formation may be regionally contingent, with the strongest enhancements occurring in regions where both temperatures and precursor emissions are already high.

Overall, these findings demonstrate that climate warming is reshaping ozone formation regimes across China, but the magnitude and direction of this reshaping vary considerably among regions, highlighting the need for region-specific ozone management strategies that account for differential climatic sensitivities.

4.5 Implications and limitations

These findings carry important implications for ozone management in China. The rapid increase in heatwave-ozone compound events and the strengthening climatic sensitivity of ozone formation suggest that emission-oriented control strategies alone may become less effective under continued warming, particularly in regions such as BTH, CEN, and EST, where meteorological drivers increasingly govern ozone variability. In these regions, climate-adaptive air-quality planning—such as incorporating meteorological forecasts into ozone early-warning systems and considering long-term warming trends in emission reduction targets—may be necessary to sustain air-quality gains.

In contrast, in regions where precursor-related factors retain substantial influence, such as PRD, continued emission reductions are likely to yield more immediate and pronounced benefits. The pronounced regional heterogeneity identified in this study further underscores the need for region-specific rather than uniform national strategies (Su et al. 2025). Future ozone mitigation policies should therefore account for both the level of anthropogenic emissions and the regional sensitivity of ozone formation to climate warming, as these two dimensions define distinct risk profiles that require

differentiated management approaches..

Several limitations should be acknowledged. First, this study primarily focused on the relationships between heatwaves, meteorological conditions, and ozone pollution, while the potential influences of large-scale atmospheric circulation patterns, such as those identified by Gao et al. (2023), were not explicitly considered. Second, although the MGWR model effectively captures spatial heterogeneity, it remains fundamentally a linear regression framework; ozone formation involves complex nonlinear interactions that may not be fully represented. Third, the present analysis focused on historical changes during 2000-2024 and did not explicitly evaluate future climate scenarios. Future studies should integrate climate-model projections, chemical transport models, and explainable machine-learning approaches to better characterize nonlinear climate-air pollution interactions and quantify future changes in ozone risks under different warming pathways.

5. Conclusion

Using CN05.1 temperature observations, CHAP ozone datasets, ERA5 reanalysis products, conditional probability analysis, and multiscale geographically weighted regression (MGWR), this study investigated the spatiotemporal evolution of heatwaves, ozone pollution, and heatwave-ozone compound events across China during 2000-2024, as well as the heterogeneous drivers of ozone variability in six major urban agglomerations. The main conclusions are as follows.

(1) Heatwaves, ozone pollution, and heatwave-ozone compound events all exhibited significant increasing trends across China during the study period. Nighttime heatwaves (NHWs) and compound heatwaves (CHWs) increased more rapidly than daytime heatwaves (DHWs), indicating an accelerating shift toward persistent and continuous thermal extremes. Ozone pollution displayed a pronounced east-west gradient, with hotspots concentrated in the North China Plain and the Yangtze River Delta. Heatwave-ozone compound events expanded substantially after 2015 and spread beyond traditional hotspot regions, suggesting a nationwide increase in compound climate-air pollution risks.

(2) Heatwaves significantly increased the probability of ozone pollution, although the magnitude of enhancement varied among heatwave types and urban agglomerations. Daytime heatwaves exerted the strongest promoting effect on ozone occurrence, highlighting the dominant role of daytime photochemical processes in ozone formation. Compound heatwaves further increased ozone exposure by

prolonging favorable meteorological conditions over consecutive days. Regional differences were evident, with Beijing-Tianjin-Hebei exhibiting the highest conditional ozone probabilities, while the Chengdu-Chongqing urban agglomeration showed the strongest relative enhancement effects under heatwave conditions.

(3) Ozone pollution exhibited significant spatial dependence and pronounced regional heterogeneity across all six urban agglomerations. Global Moran's I values were positive and statistically significant in both 2010 and 2020, indicating persistent spatial clustering of ozone concentrations. MGWR results further revealed substantial differences in T_{max} sensitivity among regions. Temperature sensitivity increased markedly in Beijing-Tianjin-Hebei, Central China, and Eastern China, indicating that ozone formation in these highly urbanized regions has become increasingly responsive to climate warming. In contrast, T_{max} sensitivity weakened in Northeast China, suggesting that ozone formation remains constrained by relatively low background temperatures and weaker photochemical activity.

(4) Meteorological factors consistently dominated ozone variability across the six urban agglomerations. Maximum temperature (T_{max}) and solar radiation emerged as the most important positive drivers of ozone concentrations, whereas relative humidity generally exerted the strongest inhibitory effect. Between 2010 and 2020, the influence of meteorological factors strengthened in several urban agglomerations, particularly in Central China and Eastern China, where ozone formation exhibited an increasing dependence on temperature-related controls. Meanwhile, the relative importance of precursor-related factors weakened in some regions, suggesting a gradual shift toward stronger meteorological regulation under a warming climate.

(5) Overall, the results demonstrate that climate warming is reshaping ozone pollution patterns across China through two complementary pathways: increasing the frequency of heatwave-ozone compound events and strengthening the climatic sensitivity of ozone formation. As heatwaves become more frequent and persistent under future warming scenarios, climate-driven meteorological conditions may play an increasingly important role in regulating ozone variability. Therefore, future ozone mitigation strategies should integrate both emission-reduction measures and climate-adaptation policies to effectively reduce environmental and public-health risks associated with compound climate-air pollution extremes.

6. References

Ban J, Lu K, Wang Q, et al. (2022) Climate change will amplify the inequitable

- exposure to compound heatwave and ozone pollution. *One Earth* 5(6): 677-686.
- Chen H, Zhao L, Cheng L, et al. (2022a) Projections of heatwave-attributable mortality under climate change and future population scenarios in China. *The Lancet Regional Health - Western Pacific* 28: 100582.
- Chen H, Zhao L, Dong W, et al. (2022b) Spatiotemporal variation of mortality burden attributable to heatwaves in China, 1979-2020. *Science Bulletin* 67: 1340-1344.
- Chen Z Y, Petetin H, Méndez Turrubiates R F, et al. (2024) Population exposure to multiple air pollutants and its compound episodes in Europe. *Nature Communications* 15: 2094.
- Domingo N G G, Fiore A M, Lamarque J F, et al. (2024) Ozone-related acute excess mortality projected to increase in the absence of climate and air quality controls consistent with the Paris Agreement. *One Earth* 7: 325-335.
- Du H, Yan M, Liu X, et al. (2024) Exposure to concurrent heatwaves and ozone pollution and associations with mortality risk: A nationwide study in China. *Environmental Health Perspectives* 132: 047012.
- Fotheringham A S, Yang W, Kang W (2017) Multiscale geographically weighted regression (MGWR). *Annals of the American Association of Geographers* 107(6): 1247-1265.
- Gao M, Wang F, Ding Y, et al. (2023) Large-scale climate patterns offer preseasonal hints on the co-occurrence of heat wave and O₃ pollution in China. *Proceedings of the National Academy of Sciences* 120(26): e2218274120.
- Gong H, Ma K, Hu Z, et al. (2024) Attribution of the August 2022 extreme heatwave in southern China: Role of dynamical and thermodynamical processes. *Bulletin of the American Meteorological Society*.
- He G, Xu Y, Hou Z, et al. (2021) The assessment of current mortality burden and future mortality risk attributable to compound hot extremes in China. *Science of the Total Environment* 777: 146219.
- Hersbach H, Bell B, Berrisford P, et al. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* 146(730): 1999-2049.
- Hertig E, Russo A, Trigo R M (2020) Heat and ozone pollution waves in central and south Europe—characteristics, weather types, and association with mortality. *Atmosphere* 11(12): 1271.
- Huang J, Pan X, Guo X, et al. (2018) Health impact of China's Air Pollution Prevention and Control Action Plan: an analysis of national air quality

- monitoring and mortality data. *The Lancet Planetary Health* 2: e313-e323.
- IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.
- Jacob D J, Winner D A (2009) Effect of climate change on air quality. *Atmospheric Environment* 43(1): 51-63.
- Jiang L, Zhang J, Liu Q, et al. (2023) Spatiotemporal variations of the global compound heat wave and the drivers of its spatial heterogeneity. *Journal of Cleaner Production* 408: 137201.
- Kerr G H, Waugh D W, Steenrod S D, et al. (2020) Surface ozone-meteorology relationships: Spatial variations and the role of the jet stream. *Journal of Geophysical Research: Atmospheres* 125: e2020JD032735.
- Kou W, Gao Y, Zhang S, et al. (2023) High downward surface solar radiation conducive to ozone pollution more frequent under global warming. *Science Bulletin* 68: 388-392.
- Lee J B, Cha J S, Hong S C, et al. (2015) Projections of summertime ozone concentration over East Asia under multiple IPCC SRES emission scenarios. *Atmospheric Environment* 106: 335-346.
- Lee J D, Lewis A C, Monks P S, et al. (2006) Ozone photochemistry and elevated isoprene during the UK heatwave of August 2003. *Atmospheric Environment* 40: 7598-7613.
- Li H, Cao Y, Xiao J, et al. (2024a) A daily gap-free normalized difference vegetation index dataset from 1981 to 2023 in China. *Scientific Data* 11(1): 527.
- Li M, Huang X, Yan D, et al. (2024b) Coping with the concurrent heatwaves and ozone extremes in China under a warming climate. *Science Bulletin* 69(18): 2938-2947.
- Lu X, Zhang L, Wang X, et al. (2020) Rapid increases in warm-season surface ozone and resulting health impact in China since 2013. *Environmental Science & Technology Letters* 7(4): 240-247.
- Mallapaty S (2022) China's extreme weather challenges scientists trying to study it. *Nature* 609: 888.
- Mazzarella A, Palumbo A (1989) The 11-yr ozone modulation of extreme surface air temperatures. *Theoretical and Applied Climatology* 40(3): 155-160.

- Meehl G A, Tebaldi C, Tilmes S, et al. (2018) Future heat waves and surface ozone. *Environmental Research Letters* 13: 064004.
- Ren C, Williams G M, Mengersen K, et al. (2009) Temperature enhanced effects of ozone on cardiovascular mortality in 95 large US communities, 1987-2000: assessment using the NMMAPS data. *Archives of Environmental & Occupational Health* 64(3): 177-184.
- Sillman S (1999) The relation between ozone, NO_x and hydrocarbons in urban and polluted rural environments. *Atmospheric Environment* 33: 1821-1845.
- Stevens L, Phillips I D (2025) The synoptic climatology of winter and summer air pollution in Glasgow, Scotland. *Theoretical and Applied Climatology* 156(7): 358.
- Su J, Jiao L, Xu G (2025) Intensified exposure to compound extreme heat and ozone pollution in summer across Chinese cities. *npj Climate and Atmospheric Science* 8: 74.
- Tian Y, Wang Y, Han Y, et al. (2023) Spatiotemporal characteristics of ozone pollution and resultant increased human health risks in central China. *Atmosphere* 14: 1591.
- Wang L, Yang X, Dong J, et al. (2023) Evolution of surface ozone pollution pattern in eastern China and its relationship with different intensity heatwaves. *Environmental Pollution* 338: 122725.
- Wang N, Duan F, Shan L, et al. (2025) Impacts of intensified heatwaves on escalation of ozone and reactive nitrogen in summer. *Environmental Science & Technology* 59(2): 887-901.
- Wang S, Li X, Wang F, et al. (2026) Variation characteristics in compound drought-heatwave events in Northwest China and the relationship with sea surface temperature. *Theoretical and Applied Climatology* 157(1): 22.
- Watts N, Amann M, Arnell N, et al. (2021) The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *The Lancet* 397: 129-170.
- Wei J, Li Z, Li K, et al. (2022) Full-coverage mapping and spatiotemporal variations of ground-level ozone (O₃) pollution from 2013 to 2020 across China. *Remote Sensing of Environment* 270: 112775.
- Wu J, Gao X (2013) A gridded daily observation dataset over China region and comparison with the other datasets. *Chinese Journal of Geophysics* 56(4):

1102-1111.

- Wu J, Gao X, Giorgi F, et al. (2017) Changes of effective temperature and cold/hot days in late decades over China based on a high resolution gridded observation dataset. *International Journal of Climatology* 37(S1): 788-800.
- Xu J, Zhao Z, Wu Y, et al. (2023) Impacts of meteorological conditions on autumn surface ozone during 2014-2020 in the Pearl River Delta, China. *Earth and Space Science* 10: e2022EA002742.
- Xu R, Sun H, Zhong Z, et al. (2024) Ozone, heat wave, and cardiovascular disease mortality: A population-based case-crossover study. *Environmental Science & Technology* 58: 171-181.
- Xu X L (2017) China GDP spatial distribution kilometer grid dataset. Resource and Environmental Science Data Registration and Publishing System. DOI: 10.12078/2017121102.
- Xu Y, Gao X, Shen Y, et al. (2009) A daily temperature dataset over China and its application in validating a RCM simulation. *Advances in Atmospheric Sciences* 26(4): 763-772.
- Yan D (2024) Anthropogenically and meteorologically modulated summertime ozone trends and their health implications since China's clean air actions. *Environmental Pollution* 343: 123234.
- Yang X, Zeng G, Iyakaremye V, et al. (2022) Effects of different types of heat wave days on ozone pollution over Beijing-Tianjin-Hebei and its future projection. *Science of the Total Environment* 837: 155762.
- Yang Z, Li Z, Cheng F, et al. (2025) Two-decade surface ozone (O₃) pollution in China: Enhanced fine-scale estimations and environmental health implications. *Remote Sensing of Environment* 317: 114459.
- Yu W, Ye T, Zhang Y, et al. (2023) Global estimates of daily ambient fine particulate matter concentrations and unequal spatiotemporal distribution of population exposure: a machine learning modelling study. *The Lancet Planetary Health* 7: e209-e218.
- Zong L, Yang Y, Xia H, et al. (2022) Joint occurrence of heatwaves and ozone pollution and increased health risks in Beijing, China: role of synoptic weather pattern and urbanization. *Atmospheric Chemistry and Physics* 22(10): 6523-6538.

7. Statements & Declarations

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Authors' contributions

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Xinying Qin: Writing - review & editing.

Yulu He: Data curation, Methodology, Writing - review & editing.

Yijia Yin: Writing - review & editing , Visualization.

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Data availability Data and materials are open sources, available on the website

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SILongTermChangesinHeatwaveOzoneCompoundEventsandSpatiallyHeterogeneousOzoneAssociationsacrossChina.docx](#)