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Key Points:

- Co-occurrence of heat and ozone is increasing during recent heatwave events in China
- Ozone modification worsens heat-related health risks especially during heat-ozone events
- Future changes in heatwave-related mortality will be amplified by ozone modification

Supporting Information:

Supporting Information may be found in the online version of this article.

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Modification Effect of Ozone on Current and Future Health Burden Associated With Short-Term Heatwave Exposure in China

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Abstract The co-occurrence of heatwave (HW) and ozone pollution in China has increased significantly. Epidemiological studies indicate that ozone can modify the association between heatwaves and premature mortalities but quantitative health impacts remain poorly understood. This study evaluates premature cardiovascular mortalities attributable to short-term heatwave exposure during warm seasons across China during 2013–2022 by integrating a widely-used health impact assessment model with high-resolution ERA5 meteorological data and TAP ozone concentrations, and quantitatively assesses the modifying effect of ozone on HW-related mortality for the first time at the national scale. Future ozone-modified health burden under different scenarios is also quantified by using multi-model simulations from CMIP6. Ozone-modified HW-related premature deaths increased from 1.8 thousand persons (95% CI: 0.5–3.3 thousand persons) in 2013 to 7.3 thousand persons (95% CI: 1.8–12 thousand persons) in 2022, with the modifying contribution becoming positive since 2017. Age-specific ozone-modified effects were negative for individuals aged ≥ 75 years and positive for those ≤ 64 years. Traditional exposure-response analyses ignoring ozone modification will underestimate HW-related health hazards but overestimate health damage in the elderly. Future HW-related premature mortalities are projected to decrease by 392 persons (95% CI: 191–610 persons) under SSP1-2.6 but increase by 1726 persons (95% CI: 912–2528 persons) under SSP3-7.0 in 2060 compared to 2022. When ozone modification is considered, these changes are amplified by 43.9% and 8.4%, respectively. All results indicate that sustained improvements in ozone air quality can reduce the modifying effect of ozone in the future.

Plain Language Summary Heatwaves and ozone pollution are dangerous on their own, but they are even worse when they happen together. Scientists often study these two events separately. However, high temperature and high ozone frequently occur at the same time, creating a combined health threat that is greater than the sum of its parts. We analyzed 10 years of detailed data across China to understand how ozone makes heatwaves deadlier. We found that heatwaves with high ozone are becoming more frequent in recent years. Since 2017, ozone has significantly increased the health risks associated with heatwaves. Interestingly, traditional exposure-response analysis without ozone modification will underestimate heatwave-related health hazards but overestimate health damage to the elderly. We also projected future risks. If China follows a sustainable path with lower emissions, heatwave-related deaths will decrease. However, in a high-emission future, deaths will surge, and ozone will make the situation much worse. This study shows that to protect public health, we must consider ozone pollution when addressing heatwaves. Controlling ozone is not just about improving air quality; it is also a vital way to reduce the deadly impact of extreme heat.

1. Introduction

In recent years, the rate of global warming has increased significantly. According to the IPCC Sixth Assessment Report, the average global temperature over the past decade was approximately 1.1 K higher than the pre-industrial level for the period 1850–1900 (Pörtner et al., 2022). As one of the countries most severely affected by climate change, China experienced an annual mean surface temperature rise by 0.26 K per decade between 1951 and 2020, a rate notably exceeding the global average during the same period (CMA Climate Change Centre, 2021). With the intensification of climate change, the frequency and intensity of heatwave (HW) events

are projected to increase continuously. Concurrently, health risks associated with heatwaves have drawn growing attention. Numerous epidemiological studies have demonstrated that prolonged exposure to high temperature can lead to various health risks, including cardiovascular and respiratory diseases (Bell et al., 2024; Ye et al., 2012). The Lancet Countdown China report indicates that, compared with the period 1986–2005, the number of HW-related deaths in China increased by 1.9 times between 2019 and 2023 and is projected to rise further to approximately 29000–38000 by 2060 (Romanello et al., 2024).

Ozone (O_3) is a primary air pollutant in China, formed through photochemical reactions between volatile organic compounds (VOCs) and nitrogen oxides (NO_x) under sunlight. Its concentration exhibits a strong positive correlation with air temperature (Atkinson, 2000), indicating that O_3 pollution may intensify under ongoing global warming. Consequently, O_3 pollution and heatwaves will occur simultaneously, potentially leading to concurrent exposure that can exacerbate adverse health effects through synergistic mechanisms (Schnell & Prather, 2017). Epidemiological evidence has consistently shown that exposure to either heatwaves or ozone alone can cause a health burden associated with cardiovascular and respiratory diseases (Anenberg et al., 2010; Sun et al., 2020; Yan et al., 2013; Yang et al., 2019; Yin et al., 2017). A recent study explored the synergistic effects of air pollution and atmospheric temperature on human health, revealing that elevated air temperature can intensify the adverse health impacts of ozone (Anenberg et al., 2020). This conclusion is consistent with the finding of Chen et al. (2018), which showed a similar outcome summarized across eight European regions—specifically, that health risks associated with heat exposure rise significantly during periods of severe O_3 pollution. These studies indicate that simultaneous exposure to heatwaves and ozone exerts a significant synergistic impact on human health, with the associated health risks substantially exceeding those of exposure to either stressor alone (Du et al., 2024).

In previous research investigating the health risks of combined heatwave and ozone exposure, two parallel lines of epidemiological evidence have emerged. The first line evaluates how air temperature modifies the health burden associated with ozone. Shi et al. (2020) conducted a time-series analysis across 128 Chinese counties to investigate how air temperature modifies O_3 -related mortality. Their results indicated that high-temperature conditions significantly enhance the impact of ozone exposure on the risk of non-accidental mortality. Specifically, for every $10 \mu\text{g m}^{-3}$ increase in ozone concentration during the high-temperature period, the risk of non-accidental mortality increased by 0.44% (95% CI: 0.36%–0.51%). Chen et al. (2021) investigated the relationship between air temperature and health risk associated with O_3 exposure over the North China Plain from 2013 to 2018 by using a time series approach and a two-stage statistical model incorporating temperature modification and interaction effects. Their analysis revealed that, without accounting for temperature modification, the short-term O_3 exposure effect on non-accidental mortality is 0.15% (95% CI: 0.09%–0.21%) per $10 \mu\text{g m}^{-3}$ increase in O_3 concentration. However, when the temperature-modifying effect is considered, the mortality risk associated with O_3 exposure under the high-temperature condition significantly increases to 0.57% (95% CI: 0.43%–0.71%). These studies have demonstrated that air temperature exerts a regulatory influence on O_3 concentration and its association with mortality. Specifically, as air temperature increases, the adverse health effects of O_3 exposure become more pronounced (Li et al., 2017; Xu et al., 2024).

The second line of investigation, which is more directly relevant to our study, examines how ozone modifies the health burden associated with short-term exposure to heatwaves. For example, Qi et al. (2023) conducted a systematic evaluation of the potential modifying effects of O_3 during the warm season on HW-related health impacts, using data—including mortality rates for cardiovascular diseases, chronic heart diseases, and cerebrovascular diseases—from 250 Chinese cities from 2015 to 2019. Their results revealed that high concentrations of O_3 significantly amplify the impact of HW on cerebrovascular disease mortality. To date, fewer studies have quantified the number of ozone-modified heatwave-related premature deaths across China, nor the temporal trend of such modifying contribution. Meanwhile, future projections indicate that as human activities intensify, the frequency of compound events involving concurrent HW and O_3 pollution will increase (Li et al., 2024). Therefore, there is an urgent need to improve the understanding of the role of ambient ozone in shaping the health burden associated with HW exposure. In this study, the term “modifying effect of ozone” (or “ozone modification”) refers to the change in the strength of the association between heatwave exposure and cardiovascular mortality across different levels of ozone concentrations, that is, effect modification in the epidemiological sense. This is distinct from the co-occurrence of heatwave and ozone events.

To quantify the health burden attributable to heatwave exposure and assess the modifying contribution of ozone, this study employs a widely used health impact assessment model (Chen et al., 2022) combined with high

spatiotemporal resolution meteorological data from ERA5 (European Centre for Medium-Range Weather Forecasts Fifth Generation Reanalysis) and ozone concentrations from TAP (Tracking Air Pollution in China) data set. The study aims to estimate the number of premature cardiovascular disease deaths caused by short-term HW exposure in China during warm seasons (May–September) from 2013 to 2022, as well as the modifying effect of ozone on the associated health risks. Additionally, future O₃-modified HW-related health impacts under different scenarios of SSP1-2.6 and SSP3-7.0 in 2030 and 2060 are also quantified using simulation outputs from Coupled Model Intercomparison Project Phase 6 (CMIP6). All the conclusions may contribute to a clear understanding of synergistic health risks associated with HW and ozone exposure, facilitate the development of integrated mitigation strategies for HW and air pollution, and provide empirical evidence for the refinement of relevant policies and health indicators.

2. Data and Methods

2.1. Data Set of Temperature and Ozone

The near-surface air temperature across China from 2013 to 2022 is obtained from ERA5 (ECMWF, 2023), with a temporal resolution of 1 hr and a spatial resolution of 0.25°. The national maximum daily 8-hr average ozone (MDA8 O₃) concentrations for the same period are sourced from the TAP data set (Tracking Air Pollution, 2023). The TAP data set integrates multi-source data including numerical simulation outputs (WRF-CMAQ), monitoring observations (CNEMC), and satellite remote sensing (OMI), characterized by high spatiotemporal resolution of 1 day and 0.1° (Xiao et al., 2022; Xue et al., 2020).

Future air temperature and MDA8 O₃ concentration projections for the year 2030 and 2060 are derived from five different CMIP6 models (CESM2-WACCM, GFDL-ESM4, UKESM1-0-LL, MIROC-ES2H, and EC-Earth3-AerChem) under two representative SSP scenarios (SSP1-2.6 and SSP3-7.0, representing sustainable development and regional rivalry pathways, respectively). The multi-model ensemble mean is calculated to reduce biases among different models. The years 2030 and 2060 are selected to align with China's dual-carbon goals (carbon peak by 2030 and carbon neutrality by 2060), while SSP1-2.6 and SSP3-7.0 represent low- and high-emission pathways that bracket plausible future trajectories without overamplifying uncertainty.

The definition of a heatwave follows the approach proposed by Yin et al. (2018), who define a heatwave as at least two consecutive days with daily mean air temperature exceeding the 97.5th percentile of the daily temperatures during the study period. Specifically, the 97.5th percentile threshold was calculated for each grid cell individually based on the daily mean temperature distribution of that grid cell during the study period, rather than using a single uniform threshold for the whole country. This approach accounts for the significant spatial heterogeneity in temperature climatology across China. For the historical period, the 97.5th percentile daily mean temperature is derived from the period of 2013–2022. To ensure the temporal consistency for the future period, the 97.5th percentile values for the years 2030 and 2060 are selected from 2025 to 2034 and 2055–2064, respectively.

For the health impact assessment, daily MDA8 O₃ concentrations are categorized into low, medium, and high levels based on location-specific tertiles. The tertile cutoffs are defined as the 33rd and 66th percentiles of the ozone concentration distribution for each grid cell, calculated separately using warm-season data (May–September) to account for seasonal and spatial variations. These cutoffs remain fixed for the analysis period. In the main analysis, the 4-day moving average of ozone concentrations (lag0–3, i.e., the mean of the current day and the previous 3 days) is used as the exposure metric. This choice is justified by prior studies (e.g., Qi et al., 2023) which demonstrated that a 4-day moving average captures both acute and short-term cumulative effects of ozone on health outcomes.

2.2. Data Set of Population and Age Structure

The gridded age-specific population data for China from 2013 to 2022 are obtained from LandScan (Oak Ridge National Laboratory, 2022), and are further updated by using provincial age-specific demographic data from the China Statistical Yearbook (National Bureau of Statistics of China, 2023). The age structure is divided into 18 groups (0–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84, and 85+), with final aggregation into three segments (under 64, 65–74, and over 75) based on baseline mortality data. Figure S1a in Supporting Information S1 illustrates the demographic changes across

the three age groups in China from 2013 to 2022, revealing a consistent increase in the population aged 65 and above, which rises from 9.6% in 2013 to 14.8% in 2022.

Future age-specific population projections for the years of 2030 and 2060 are sourced from Population Pyramid (United Nations Department of Economic and Social Affairs Population Division, 2022). In order to generate a gridded population, we adopt the approach of Chen et al. (2023), assuming a constant proportional distribution of each grid's population relative to the national total from 2022 to 2060. Thus, the future gridded age-specific population can be generated by multiplying national age-specific populations with the gridded proportional distribution in 2022. Figure S1c in Supporting Information S1 presents projected changes in total population and age-group proportions for 2030 and 2060 relative to those in 2022. The analysis indicates a noticeable decline (−27 million in 2030 and −290 million in 2060) in total population compared to 2022. However, the proportion of the elderly older than 75 is projected to increase significantly, rising from 5.0% in 2022 to 7.0% in 2030 (20.0% in 2060).

2.3. Data Set of Baseline Mortality Rate

The age-specific baseline mortality rates (BMRs) for cardiovascular diseases in China from 2013 to 2022 are obtained from the Global Burden of Disease Study (Institute for Health Metrics and Evaluation, 2021). The latest baseline mortality data provided by the research center extends only to 2021; therefore, the 2022 BMRs in this study are based on the 2021 data. Figure S1b in Supporting Information S1 shows the changes in age-specific BMRs from 2013 to 2022. With the improvement in healthcare standards, the BMRs for cardiovascular diseases across all age groups declined. Among them, the elderly people older than 75 experience the largest decrease, with a reduction of approximately 24 deaths per thousand from 2013 to 2022.

The projected future age-specific BMRs are sourced from WHO (Mathers, 2022). Figure S1d in Supporting Information S1 compares the BMRs for the three age groups in the years 2022, 2030, and 2060. It reveals that compared to 2022, the BMRs of all three age groups in 2030 and 2060 are projected to decline significantly. Notably, the BMR of individuals aged 75 and older shows a more substantial reduction, with 156 deaths per thousand in 2030 and 159 deaths per thousand in 2060.

2.4. Health Impact Assessment Model of Short-Term Exposure to Heatwave

To assess the adverse effects of short-term heatwave exposure on cardiovascular health, we adopt the methodology proposed by Chen et al. (2021) to quantify monthly premature deaths attributable to cardiovascular diseases during heatwave periods in the warm season from May to September. These monthly estimates are then aggregated to derive the annual total premature mortality from 2013 to 2022. The specific calculation formula is as follows:

$$\text{Mort}_{y,p} = \sum_{m=5}^9 \text{Pop}_{d,y,p} \times \text{BMR}_{d,m,y,p} \times \text{HW}_{m,y,p} \times \text{AF}_{d,y,p} \quad (1)$$

where $\text{Mort}_{y,p}$ represents the number of premature cardiovascular deaths due to short-term heatwave exposure in grid p and year y ; $\text{Pop}_{d,y,p}$ denotes the population size in grid p , age group d , and year y ; m represents the month from May to September, with $m = 5$ indicating the starting time of the warm season; $\text{BMR}_{d,m,y,p}$ refers to the baseline mortality rate of cardiovascular diseases in grid p , age group d , month m , and year y ; $\text{HW}_{m,y,p}$ is the total number of heatwave days in grid p , month m , and year y ; and $\text{AF}_{d,y,p}$ denotes the heatwave-attributable fraction in grid p , age group d , and year y . The calculation formula of heatwave-attributable fraction is as follows:

$$\text{AF}_{d,y,p} = (\text{RR}_{d,y,p} - 1) / \text{RR}_{d,y,p} \quad (2)$$

where $\text{RR}_{d,y,p}$ represents the relative risk coefficient for year y , grid p , and age group d .

According to the relative risk coefficients proposed by Qi et al. (2023), two sensitivity experiments—with and without ozone modification effects—are designed (Table 1). In the BaseCase experiment (i.e., without accounting for the modifying effects of ozone on heatwave-related health risks), heatwaves are significantly positively associated with overall cardiovascular mortality, with relative risks (RRs) of 1.024 (95% CI: 0.991–1.059) for

Table 1
Relative Risk Values Under Different Ozone Modification Scenarios

Experiment	Description	Age group	Relative risk (95% CI)		
BaseCase	Without ozone modification	<64	1.024 (0.991, 1.059)		
		65–74	1.074 (1.041, 1.109)		
		>75	1.042 (1.022, 1.062)		
			Ozone level		
			Low (<33rd ^a)	Medium (33rd-66th ^a)	High (>66th ^a)
OzoneCase	With ozone modification	<64	0.990 (0.930, 1.054) ^b	1.050 (1.001, 1.102)	1.028 (0.987, 1.071)
		65–74	1.071 (1.011, 1.136)	1.076 (1.027, 1.126)	1.074 (1.034, 1.116)
		>75	1.024 (0.989, 1.061)	1.037 (1.008, 1.067)	1.045 (1.021, 1.070)

^aThe 33rd and 66th percentiles represent the concentration of MDA8 O₃ at the 33rd and 66th percentiles, respectively.

^bRR < 1 indicates that there is no evidence to confirm the health impact of short-term exposure to heatwave.

individuals under 64 years, 1.074 (95% CI: 1.041–1.109) for those aged 65–74 years, and 1.042 (95% CI: 1.022–1.062) for those over 75 years. In the OzoneCase experiment (i.e., considering the ozone-modifying effect on heatwave-associated health risks), the RR values under low ozone concentrations (below the 33rd percentile) are 0.990 (95% CI: 0.930–1.054), 1.071 (95% CI: 1.011–1.136), and 1.024 (95% CI: 0.989–1.061) for the three age groups, respectively; under medium ozone concentrations (33–66th percentile), the RR values are 1.050 (95% CI: 1.001–1.102), 1.076 (95% CI: 1.027–1.126), and 1.037 (95% CI: 1.008–1.067); and under high ozone concentrations (above the 66th percentile), the RR values are 1.028 (95% CI: 0.987–1.071), 1.074 (95% CI: 1.034–1.116), and 1.045 (95% CI: 1.021–1.070).

The impact of ozone modification on the health burden of short-term heatwave exposure can be quantified by comparing premature mortality estimates between OzoneCase and BaseCase (i.e., OzoneCase minus BaseCase).

3. Results

3.1. Co-Occurrence of Heat and Ozone has Been Increasing During Recent Heatwave Events in China

Spatial-temporal variations of heatwave (HW) days under different ozone levels during warm seasons (i.e., May–September) from 2013 to 2022 are first analyzed, as a foundation for subsequent quantitative investigation of the modification effect of ozone on health impacts of short-term heatwave exposure.

As shown in Figure 1a, the annual average number of HW days in China exhibits significant interannual variability from 2013 to 2022, with a positive trend of +0.3 days yr^{−1}. The number of national-averaged HW days is approximately 3 days. During these HW periods, the concentration of MDA8 O₃ increased by +1.8 μg m^{−3} yr^{−1}, with the 10-year-mean of 105.8 μg m^{−3}, higher than the WHO short-term air quality guideline threshold of 100 μg m^{−3} for ozone, indicating a significant and non-negligible deterioration in O₃ pollution during the recent heatwave events.

Figure 1b shows the yearly proportions of three O₃-specific (i.e., low (<33rd), medium (33rd–66th), and high (>66th) MDA8 O₃ levels) HW days. The data indicate a decrease in the proportion of HW days with low MDA8 O₃ concentrations by a rate of −5.5% yr^{−1}, while the fraction of HW days with high ozone levels has risen from 11.6% in 2013 to 63.9% in 2022, highlighting a significant increase in the co-occurrence of heat and ozone extremes during heatwaves. This rise may be attributable to warmer temperatures accelerating ozone photochemistry and unbalanced precursor emission reductions (strong NO_x cuts without effective VOCs controls).

Spatial distributions of O₃-specific HW days are presented in Figure 1c. Compared with HW conditions under low ozone level, more severe consequences can be found in double high events, with the national-mean 10-year-accumulated HW days increasing from 4.6 to 16.0 days, and the population exposure increasing from 0.5 × 10¹⁰ persons × days to 2.4 × 10¹⁰ persons × days, emphasizing the enhanced high-temperature hazards with high concentrations of MDA8 O₃.

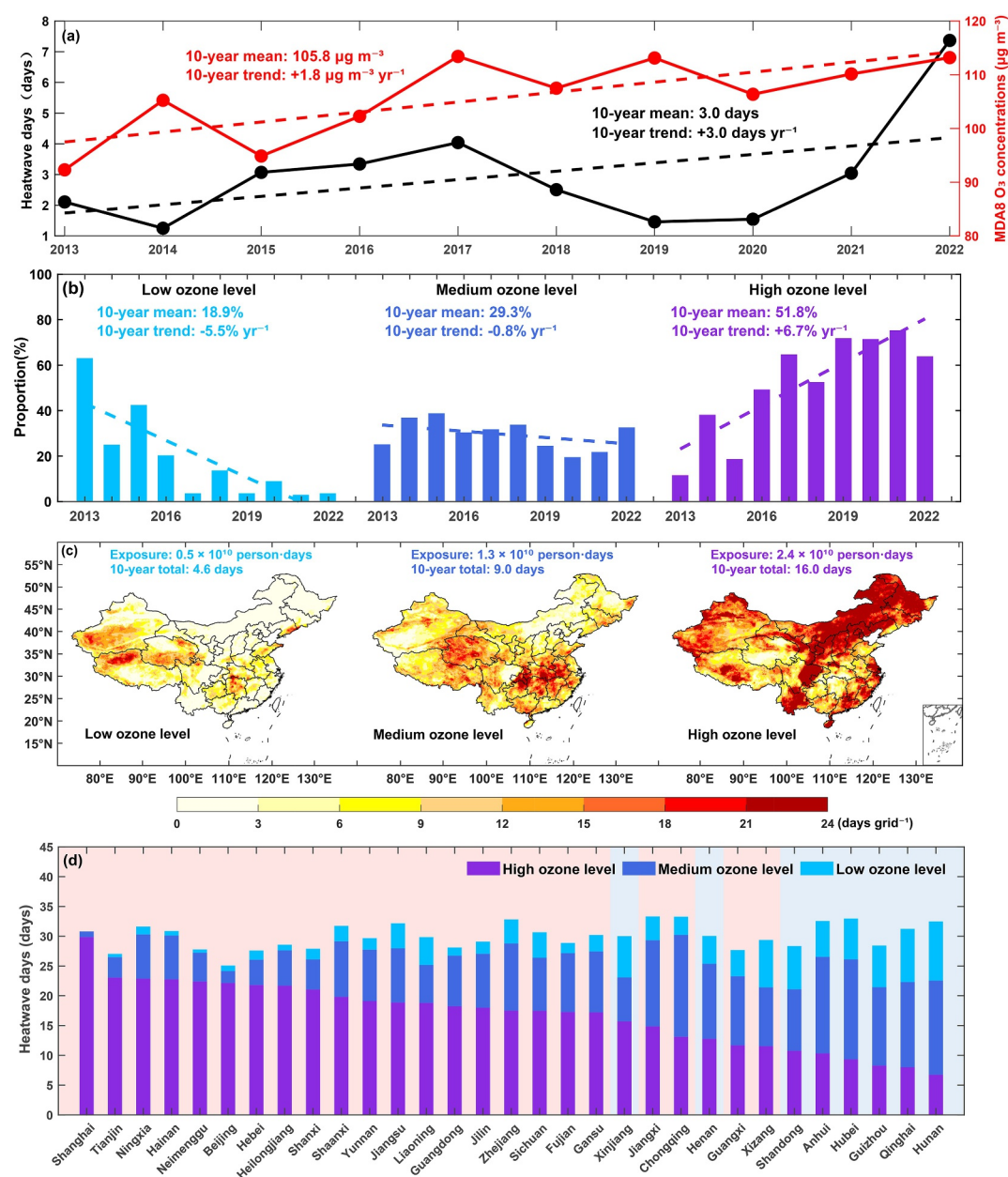


Figure 1. Spatial-temporal distribution of O_3 -specific heatwave (HW) days across China during warm season from 2013 to 2022. (a) Yearly variation of national averaged HW days (black dotted line) and the corresponding MDA8 O_3 concentrations (red dotted line). (b) Yearly proportions of HW days under low MDA8 O_3 level (0-33rd percentiles), medium MDA8 O_3 level (34-66th percentiles), and high MDA8 O_3 level (67-100th percentiles), respectively. (c) Spatial distribution of 10-year-accumulated HW days under the three O_3 -specific levels. The number of the national population exposed to O_3 -specific HW is also shown. (d) O_3 -specific 10-year-accumulated HW days across 31 provinces of China. The light red (blue) background indicates increased (decreased) HW-related health hazards when the O_3 -modified effect is considered as shown in Figure 3b.

Provincial-level analysis (Figure 1d) reveals that while the number of HW days is comparable across all provinces, the proportional characteristics across the three ozone levels differ markedly. Western (e.g., Qinghai) and central (e.g., Hunan) provinces exhibit high proportion ($\sim 25\%$) of low- O_3 -level HW days. In contrast, more than 95% of HW days at metropolitan areas such as Shanghai, Beijing, and Tianjin are suffering from medium or even high ozone pollution. Therefore, when quantifying health damage attributable to heatwaves, the modifying effect of ozone on HW-related mortality burden should also be considered, as the increasing frequency of co-exposure to high temperatures and elevated ozone levels.

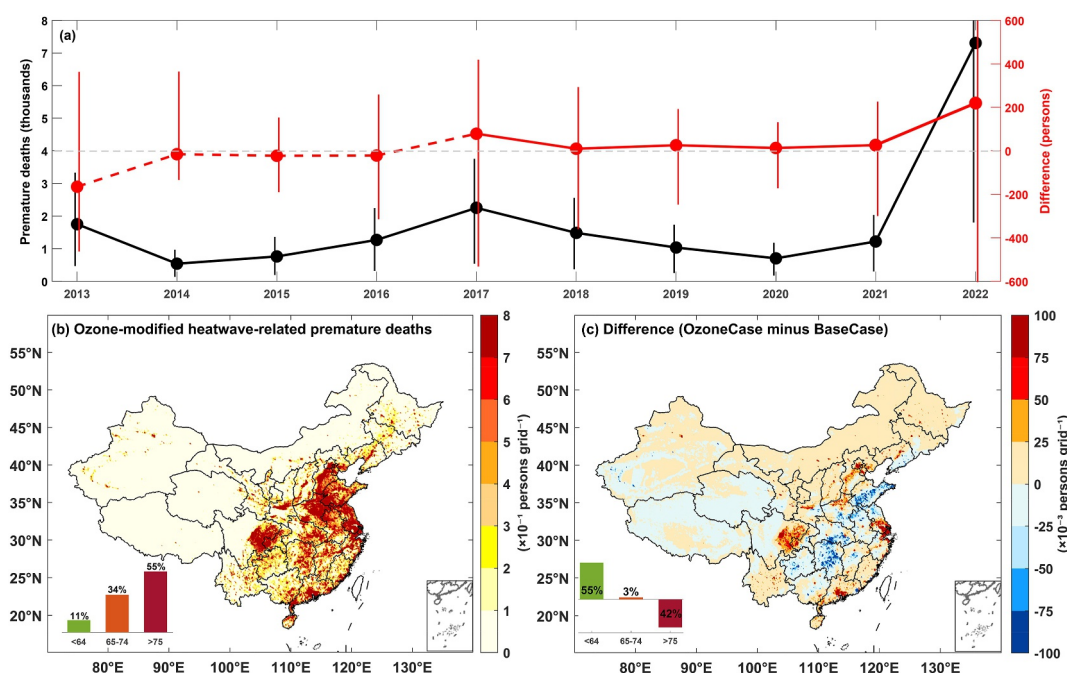


Figure 2. Spatial-temporal distribution of premature deaths due to short-term exposure to the heatwave (HW) and the contribution of the ozone-modified (O₃-modified) effects across China during the warm season from 2013 to 2022. (a) Yearly variation of national HW-related premature mortalities modified by O₃ (black dotted line) and the difference in health hazards of HW exposure with and without considering O₃ modification (red dotted line). (b) Spatial distribution of 10-year-accumulated O₃-modified short-term exposure effects of HW on health burden. The bar charts represent age-specific contributions to premature deaths. (c) Spatial distribution of the contribution of the O₃-modified effect to HW-related premature deaths. Contributions from different age groups are also shown as colored bars, representing the age-specific 10-year-accumulated contributions.

3.2. Ozone Modification Exacerbates Heatwave-Related Health Risk Especially During Concurrent Heat and Ozone Events

Figure 2 illustrates spatial-temporal distribution of premature deaths caused by short-term exposure to heatwaves and the contribution of O₃-modified effects. By analyzing Figure 2a we can find that the number of O₃-modified HW-related premature mortalities increases from 1.8 thousand persons (95%CI: 0.5–3.3 thousand persons) in year 2013 to 7.3 thousand persons (95%CI: 1.8–12 thousand persons) in year 2022, with an increasing trend of 0.3 thousand persons (95%CI: –0.1–0.8 thousand persons) per year. These HW-attributable health hazards are predominantly located over densely populated regions such as Guangdong (1528 persons (95%CI: 374–2546 persons)), Sichuan (1359 persons (95%CI: 331–2197 persons)), Henan (1269 persons (95%CI: 319–2188 persons)), Jiangsu (1158 persons (95%CI: 286–1962 persons)), and Shandong (1143 persons (95%CI: 297–2036 persons)) (Figure 3a), with the largest health impacts on elderly people older than 75 (55%), followed by individuals aged 65–74 (34%), and younger than 64 (11%), respectively (Figure 2b).

Comparison of premature cardiovascular mortalities attributable to short-term heatwave exposure with and without ozone modification enables the quantification of the modifying effects of ozone on the heatwave–mortality relationship. As shown in Figure 2a, the modifying contribution of ozone has exacerbated the health burden associated with heatwaves since 2017, as the proportion of heatwave days with high ozone levels (i.e., >66th percentile) has exceeded 50% in the years following 2017 (Figure S2a in Supporting Information S1). The largest O₃-modified effect is found in 2022 with the value of +219 persons.

From spatial distribution perspective, the positive and/or negative modification effect of ozone on HW-related premature mortalities can also be explained by the proportion of high-O₃-level HW days (Figure 2c). For example, the ozone modification effect is positive in Beijing (+10 persons), Shanghai (+17 persons), Sichuan (+59 persons), and Guangdong (+43 persons) with proportions of high-O₃-level HW days of 88.3%, 96.9%, 57.0%, and 64.9%, respectively. While in provinces such as Guizhou (–23 persons), Anhui (–14 persons), Hubei

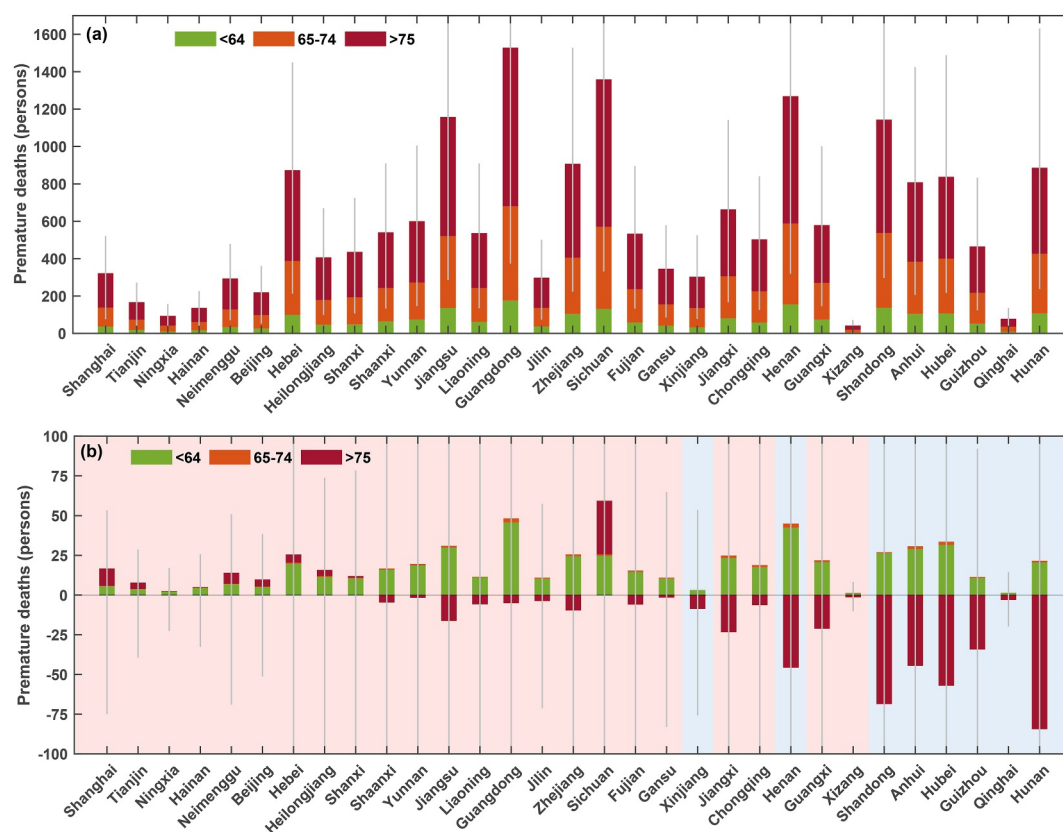


Figure 3. (a) HW-related premature deaths modified by O₃ and (b) the difference in health hazards due to short-term HW exposure with and without considering the O₃-modified effect across 31 Chinese provinces during the warm season from 2013 to 2022. The light red (blue) background indicates increased (decreased) HW-related health hazards when O₃ modification is considered.

(−24 persons), and Hunan (−63 persons) where high-O₃-level HW days account for less than one-third of total (20.8%–31.7%), the modification effects of ozone are negative (Figure 3b).

Focusing on age-specific O₃-modified effect, we can conclude that negative modification contributions are primarily attributed to older adults, with a national mean of −42% (−383 persons (95%CI: −3082–1406 persons)), while positive modification effects are mainly driven by individuals under 64 years of age, with a national mean of +55% (+504 persons (95%CI: 21–1203 persons)). This negative modification effect for the elderly is mainly driven by ozone-specific heatwave days, especially the proportion of heatwave days under low and medium ozone levels.

All results discussed above imply that traditional exposure-response analysis without considering O₃-modified effects, or treating the ozone variable merely as a confounder, will underestimate health hazards caused by heatwaves in China, especially during the periods of co-occurrence of heat–ozone extremes in recent years, but overestimate health damage for the elderly.

3.3. Future Changes in Heatwave-Related Mortality Will Be Amplified by Ozone Modification

Future changes in heatwave duration under different socioeconomic pathways, along with shifts in population size and age structure as well as improvements in healthcare, will significantly affect health risks associated with short-term heatwave exposure in China. Meanwhile, the modifying effect of ozone on HW-related health impacts is expected to change in response to variations in the frequency of high-O₃-level HW days. Therefore, a quantitative assessment of future health burdens attributable to short-term heatwave exposure, including the modifying effects of ozone, is essential.

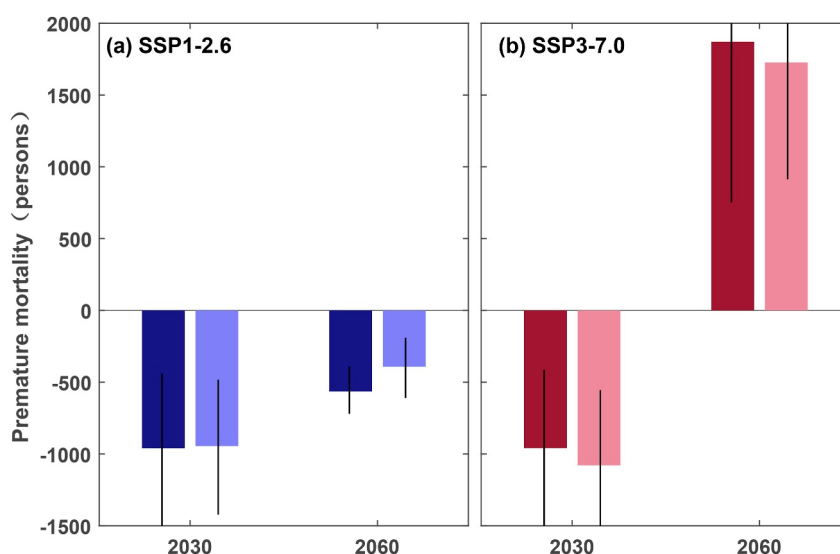


Figure 4. Future changes in premature mortalities due to short-term heatwave exposure in years of 2030 and 2060 relative to that in year 2022 under different scenarios of (a) SSP1-2.6 and (b) SSP3-7.0 with (dark-colored bars) and without (light-colored bars) considering the effect of ozone modification in China.

Under SSP1-2.6 scenario, the number of premature deaths in China attributable to short-term heatwave exposure in 2030 and 2060 shows a significant decrease compared to that in 2022 (Figure 4a). This reduction is primarily driven by the decline in baseline mortality rates (Figure S1d in Supporting Information S1). Under SSP3-7.0 scenario, the change in premature deaths from short-term heatwave exposure in 2030 is similar to that under the SSP1-2.6 scenario (Figure 4b). However, by 2060, due to the worsening aging population (Figure S1c in Supporting Information S1) and the increasing number of HW days (Figure S2b in Supporting Information S1), the number of HW-related premature deaths is projected to increase compared to 2022 levels.

Compared to health hazards without considering ozone modification, future changes—such as increases or decreases—in HW-related premature mortalities will be amplified by the modifying effect of ozone. Under the scenario of SSP3-7.0 in 2060, the number of premature deaths is projected to increase by 1726 persons (95% CI: 912–2528 persons) compared to 2022 levels without considering ozone modification. When ozone modification is taken into account, the increase rises by an additional 8.4% (+145 persons). Meanwhile, under the SSP1-2.6 scenario in 2060, the reduction in premature deaths when accounting for ozone modification (−564 persons (95% CI: −720 to −390 persons)) will be greater than that without considering ozone modification (−392 persons (95% CI: −610 to −191 persons)). All these O_3 -modified amplified changes are attributed to the high proportion of high- O_3 -level heatwave days with 68.8% for SSP1-2.6 and 46.8% for SSP3-7.0 (Figure S2b in Supporting Information S1).

4. Conclusions

In the context of climate change, heatwaves (HWs) and the associated health impacts have garnered increasing attention. Concurrently, ozone air quality tends to deteriorate during heatwaves. Epidemiological studies have demonstrated that ozone can modify the association between heatwave exposure and premature mortality. However, there is still a critical gap regarding the health impact of interactions between heatwave and ozone. This study provides the first nationwide quantification of the modifying effect of ozone on heatwave-related cardiovascular mortality in China, revealing two core innovative insights.

First, we present the first national-scale assessment that moves beyond traditional relative risk estimates to directly quantify premature deaths attributable to ozone-modified heatwave exposure. Our results show that the national annual mean number of heatwave days has increased at a rate of $+0.3 \text{ days yr}^{-1}$, accompanied by deterioration in MDA8 O_3 air quality at $+1.8 \mu\text{g m}^{-3} \text{ yr}^{-1}$ during these heatwaves, leading to a rise in double-high events from 11.6% in 2013 to 63.9% in 2022. Compared with heatwave conditions under low ozone level, the population exposed over a 10-year period increases by 380% during high-ozone heatwave days, particularly in

metropolitan regions such as Shanghai, Beijing, and Tianjin. All these results emphasize an increasing trend in the co-occurrence of heat and ozone during recent heatwaves in China. Consequently, when assessing health damage attributable to heatwave, the modifying effect of ozone on HW-related mortality should be taken into account. The 10-year averaged O₃-modified HW-related premature mortalities in China during 2013–2022 is 18.3 thousand persons (95%CI: 4.6–31.2 thousand persons). Notably, the modifying contribution of ozone shifted from negative to positive in 2017, rising from −165 persons in 2013 to +219 persons in 2022. This turning point coincided with the moment when high-ozone heatwave days first exceeded 50% of total heatwave days. This shift occurred because the net modification effect is negative under low/medium ozone conditions (dominated by the elderly) but positive under high ozone conditions (dominated by the ≤64 age group); after 2017, high-ozone heatwave days became the dominant exposure scenario. The surge in high-ozone heatwave days around 2017 was driven by an exceptionally hot summer and unbalanced precursor emission reductions. These results indicate that traditional exposure-response analyses, which ignore ozone modification, systematically underestimate heatwave-attributable health hazards while overestimating the risk for the elderly (≥75 age group). The identified turning point in 2017 carries direct implications for dynamic early-warning systems that integrate air quality and heat-health alerts.

Second, we reveal robust age-specific and scenario-dependent modification patterns. In terms of age specificity, ozone's positive modification (exacerbation) is driven mainly by the <64 age group (national mean contribution +55%, +504 persons), whereas the ≥75 group consistently shows negative modification at the national level (national mean contribution −42%, −383 persons), with near-zero contribution from the 65–74 group. This age-reversed pattern is highly robust across five alternative heatwave definitions and represents one of the most central scientific findings of this study.

Regarding future projections, future HW-related premature mortalities are projected to decrease (increase) by 392 persons (95% CI: 191–610 persons) (1726 persons (95% CI: 912–2528 persons)) in 2060 under the SSP1-2.6 (SSP3-7.0) scenarios compared to 2022 levels. When ozone modification is considered, the magnitude of the decrease (increase) will be enhanced by 43.9% (8.4%). These findings underscore that synergistic ozone-heatwave control is critical for maximizing health co-benefits under ambitious climate mitigation policies. The results provide a robust scientific basis for public health adaptation strategies in response to compound pollution under climate change, with significant implications for policy formulation.

5. Discussions and Limitations

5.1. Discussions

One of the most notable findings is the reversed age-specific ozone modification effect: positive for the ≤64 age group and negative for the ≥75 age group. This pattern arises mathematically from the RR values in Qi et al. (2023), but also invites physiological and behavioral explanations. We propose two non-mutually exclusive mechanisms. First, behavioral adaptation: elderly individuals are more likely to stay indoors, use air conditioning, and avoid peak outdoor hours during high-ozone heatwaves, thereby reducing their actual concurrent exposure (Lei et al., 2025). Second, a physiological ceiling effect: the elderly already exhibit elevated heat-attributable cardiovascular risk (BaseCase RR = 1.042); adding ozone yields a smaller relative increase because physiological stress responses may approach a plateau (Wang et al., 2025). For the ≤64 age group, higher outdoor activity and lower baseline vulnerability allow positive modification. We also tested five alternative heatwave definitions with percentiles varying among 97.5th/95th/92.5th and durations varying among 2-day/3-day. Although absolute mortality estimates vary with definition stringency, the age-specific modification pattern (positive for ≤64 and negative for ≥75) remains robust across all definitions as shown in Tables S1 and S2 of Supporting Information S1.

Compared with previous studies, direct numerical comparisons of heatwave-attributable deaths are complicated by differences in heatwave definitions, health outcomes (all-cause vs. cardiovascular), and whether ozone modification is considered. However, our estimates (e.g., 10-year average ozone-modified mortality of 18.3 thousand persons) are broadly consistent with the range reported by Chen et al. (2022) for near-term projections, and our focus on cardiovascular outcomes provides a more targeted assessment of synergistic heat-ozone health penalties than all-cause studies (e.g., Hu et al., 2025; Zhang et al., 2023). More detailed comparisons can be found in Table S3 of Supporting Information S1.

5.2. Limitations

There are some limitations in this study. China's vast territory leads to substantial regional variations in daily cardiovascular mortalities, ozone concentrations, and heatwave exposure levels. Using a nationally unified relative risk (RR) coefficient across all regions to estimate premature deaths attributable to short-term heatwave exposure may introduce biases, including in the quantified contribution of ozone modification. In the future, we will derive region-specific exposure-response relationships through statistical analyses and/or comprehensive literature reviews, enabling more precise quantification of premature deaths attributable to heatwave exposure under the modifying effects of ozone.

Additionally, assuming a constant spatial population distribution relative to 2022 ignores future urbanization and rural-to-urban migration. This may lead to overestimation of future health burdens, as rural areas often experience higher ozone levels (Sun et al., 2023). However, this simplification is widely adopted to isolate climate signals, and our qualitative conclusion that ozone modification amplifies future changes remains robust. Furthermore, our projections assume a constant exposure-response relationship, ignoring potential changes in population vulnerability (aging vs. adaptation), healthcare access (already partly captured by declining baseline mortality), and air pollution policies (which may either weaken or strengthen ozone modification under different SSP scenarios). These factors introduce uncertainty but do not alter the qualitative conclusion that ozone modification amplifies future changes in heatwave-related mortality and that high ozone levels significantly amplify heatwave-related mortality. Future work should aim to incorporate dynamic population distributions, region-specific RRs, and adaptive capacity into health impact projections to better constrain these uncertainties.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Near-surface air temperature data for China from 2013 to 2022 are available from the ECMWF ERA5 reanalysis at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>. National maximum daily 8-hr average ozone (MDA8 O₃) concentrations from 2013 to 2022 can be accessed from the Tracking Air Pollution (TAP) data set at http://tapdata.org.cn/?page_id=1144&item=o3. Gridded age-specific population data for China from 2013 to 2022 are available from LandScan at <https://landscan.ornl.gov/> and were updated using provincial demographic data from the China Statistical Yearbook at <http://www.stats.gov.cn/sj/ndsj/>. Projected future age-specific population data for 2030 and 2060 are sourced from Population Pyramid at <https://www.populationpyramid.net/china/>. Age-specific baseline mortality rates for cardiovascular diseases in China are available from the Global Burden of Disease Study at <http://ghdx.healthdata.org/gbd-results-tool>. Projected future age-specific baseline mortality rates are available from the World Health Organization (WHO) at <https://collinmathers.com/2022/05/10/projections-of-global-deaths-from-2016-to-2060/>.

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