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Future warming exacerbates heatwave-ozone compound extremes in China



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Exposure to concurrent heatwave and ozone pollution events poses a great threat to the health burden. Yet the impacts of future warming on such compound extremes and the associated health risks remain unclear. Here, using dynamic downscaling techniques and multi-model ensembles, we estimate excess deaths attributed to heatwave-ozone compound extremes from climate change under Shared Socioeconomic Pathways (SSPs). We find that, driven by future climate change, ozone pollution events in China are projected to grow by 58% by the middle of the century under SSP3-7.0, half of which are also heatwave days. Consequently, the heatwave-ozone compound event exposure rises by a factor of two, causing an additional 61,600 deaths nationwide. In highly polluted regions, such compound events outweigh single events by dominating the additional mortality from climate-induced increases in heat and ozone extremes. Our results emphasize the challenges of compound extremes and underscore the urgency of climate action and improved preparedness.

Climate extremes and air pollution would undergo significant changes in the future under a changing climate. Under global warming, extreme events such as heatwaves are likely to occur more frequently, directly jeopardizing public health^{1–3}. Heat-associated mortality increased notably in China in recent years⁴. Heatwaves are also conducive to the formation of ozone pollution, providing favorable meteorological conditions (e.g., high air temperatures and intense solar radiation) and producing more precursor emissions (e.g., biogenic emissions)^{5–8}. In China, where outdoor ozone pollution is particularly severe and the number of air pollution-related deaths is notable, the potential for climate change to exacerbate an already serious problem is of particular concern^{9–11}. Moreover, concurrent heatwave and ozone pollution events may pose potentially amplified health risks^{12,13}. As climate change intensifies in the future, the frequency of heatwaves, ozone pollution, and compound extreme events may change remarkably, bringing about concerns of climate-related health issues. Projections of such extreme changes facilitate more effective and adaptive climate strategies.

Previous studies have evaluated the impacts of future climate change on either heatwave exposure^{14–16} or ozone pollution^{17–20} individually. Research on the impacts of climate change on future air quality has focused more on the assessment of average concentrations of air pollutants than on extreme pollution events^{19,21}. These studies have relied heavily on global climate-chemistry models with coarse resolution^{17,22–25}, which have difficulty simulating mesoscale processes and tend to overestimate ozone concentrations²⁶. Yet the few studies that have applied dynamical

downscaling techniques (i.e., using global model outputs to dynamically drive regional models) have relied primarily on a single global model for downscaling^{18,19}, which raises concerns about uncertainty²⁷. In particular, few studies have simultaneously considered changes in both heatwaves and ozone pollution due to future climate change under the same scenario and evaluated the contributions of heatwaves to high ozone pollution events. Moreover, the potential health burden of concurrent heatwave-ozone extremes in a warming climate remains insufficiently recognized and is rarely quantified. Yet, policymakers and the public are more concerned about extreme events, and heatwave-ozone compound extremes pose enormous challenges to the management of the atmospheric environment and public health.

Here, we comprehensively assessed the impacts of future climate change on heatwave-ozone compound extremes and the associated health risks in China. Details of our analytic approach are described in the “Methods” section. In summary, we first develop a climate and air quality modeling system based on dynamic downscaling techniques and multi-model ensembles, coupling the Coupled Model Intercomparison Project Phase 6 (CMIP6) global model outputs^{28,29} and the regional Weather Research and Forecasting model coupled to Chemistry (WRF-Chem) model. We perform simulations of the changing climate for the historical period 2010–2014 and the future period 2056–2060 under two shared socioeconomic pathway (SSP) scenarios (SSP1-2.6 and SSP3-7.0; representing a low-emission scenario and a high-emission scenario,

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respectively)³⁰. The impacts of future climate change on heatwave exposure and ozone pollution in China are assessed from downscaling simulations with multi-model ensembles under constant current air pollutant emissions, which provide the mean and range of future projections. We analyze changes in heatwaves, ozone pollution events, and compound events in a warming climate, and further evaluate the associated health impacts based on epidemiological models.

Results

Exacerbated heatwave events and ozone pollution in a warming climate

Surface temperatures show widespread increases in China from 2010–2014 to 2056–2060, with the SSP3-7.0 scenario showing a higher warming than the SSP1-2.6 scenario (Figs. S1 and S2). The temperature rise is stronger in northern China than in southern China (Fig. S1). In a warming climate, the frequency and intensity of extreme high temperature days increase significantly. Heatwaves are defined here as events lasting three or more consecutive days with daily maximum temperatures exceeding the 95th percentile of the historical baseline period, subject to a minimum threshold of 30 °C³¹. Heatwave exposure is estimated to rise by a factor of 1.5, with an absolute increase of 17 (multi-model range: 5–23) days per year over China by mid-century under SSP3-7.0 (Fig. 1A and Table S1), while the occurrence of heatwave days increases by 80% under SSP1-2.6 (Fig. 1B). A widespread increase in the number of heatwave days is projected across most of China, with larger increase in parts of northwestern and southern China.

As a result of climate change at mid-century, warm-season ozone levels increase significantly across the majority of China under SSP3-7.0, and the multi-model results show consistent increments (Fig. S3 and Fig. S4). Enhanced ozone pollution is particularly evident in highly polluted and densely populated areas such as Beijing-Tianjin-Hebei region (BTH),

Yangtze River Delta (YRD), and Fenwei Plain (FWP). Population-weighted ozone concentrations during the warm season are expected to increase by roughly 10–16 $\mu\text{g}/\text{m}^3$ in these city clusters. In contrast, under the SSP1-2.6 scenario, ozone levels increase in eastern China but decrease in western China (Fig. S3). Thus, population-weighted average warm-season ozone concentrations in China increase by 9.5 (6.8–11.2) $\mu\text{g}/\text{m}^3$ (9%; 6%–10%) and 1.9 (0.1–3.9) $\mu\text{g}/\text{m}^3$ (2%; 0%–4%) in SSP3-7.0 and SSP1-2.6 scenarios, respectively (Fig. S4).

In eastern China, where ozone precursor emissions are abundant, the climate penalty on ozone is particularly pronounced, arising from the combined effects of altered meteorological factors such as rising surface temperature, compressed boundary layer, and weakened atmospheric diffusion (Fig. S5), and enhanced precursor emissions (e.g., biogenic emissions)^{32–34}. These compounded impacts facilitate the formation of ground-level ozone and lead to more severe ozone pollution in a warming climate. Along with rising seasonal average ozone levels, high ozone pollution episodes become more frequent as a result of climate change. As climate change progresses by mid-century under SSP3-7.0, the number of ozone pollution days (i.e., daily maximum 8-h ozone [MDA8] concentration higher than 160 $\mu\text{g}/\text{m}^3$) in China is projected to increase by about 13 (10–16) days per year (58%) (51%–73%), with the increase in the BTH region and the YRD region up to 18–20 days per year (Fig. 1C and Fig. S4). Under the SSP1-2.6 scenario, the number of ozone pollution days is projected to increase slightly by 2 days (10%) in China (Table S1).

Intensified heatwave-ozone compound extremes

Climatic change is likely to escalate the exposure threat of heatwave-ozone compound extremes (concurrent heatwave and ozone pollution events). There is a greater probability of high ozone levels during extreme heatwave days, suggesting that heatwaves play an important role in driving ozone

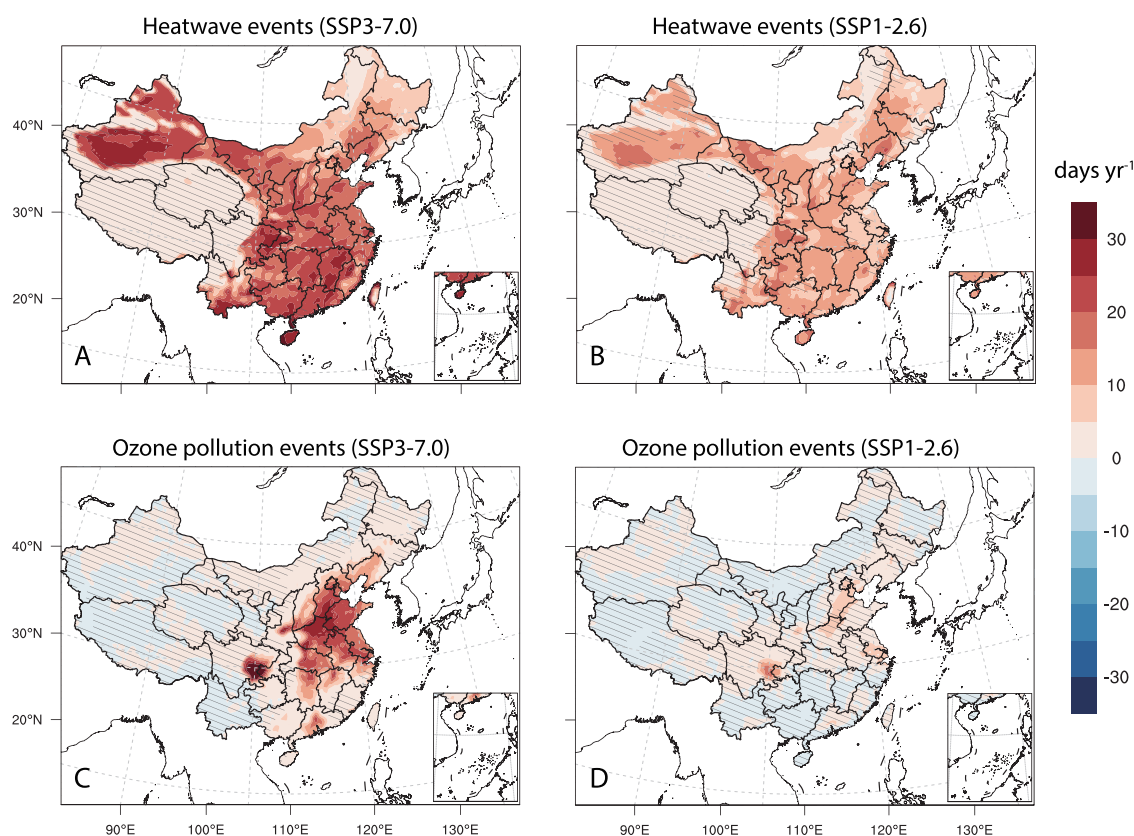


Fig. 1 | Future changes in heatwave and ozone pollution events over China driven by climate change. Projected changes in the frequency of heatwave events (A, B) and ozone pollution events (C, D) due to climate change under the SSP3-7.0 scenario and the SSP1-2.6 scenario in the future period (2056–2060) relative to the historical

period (2010–2014). Multi-model mean changes are shown. No overlay indicates regions where at least 80% of the models agree on the sign of the change; diagonal lines indicate opposite regions.

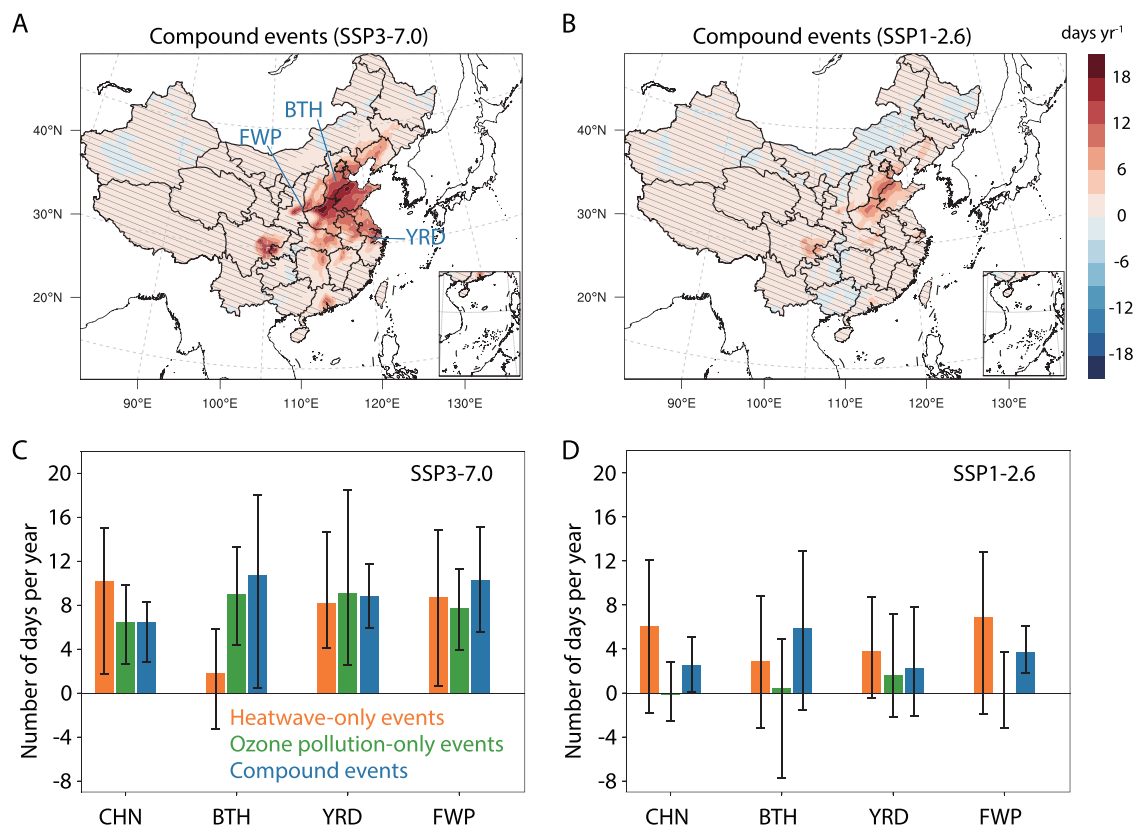


Fig. 2 | Future changes in heatwave-ozone compound extreme events and single extreme events over China driven by climate change. **A, B** Spatial distribution of changes in the frequency of compound events due to climate change under the SSP3-7.0 scenario and the SSP1-2.6 scenario in the future period (2056–2060) relative to the historical period (2010–2014). **C, D** Projected changes in the frequency of compound events and two single events (heatwave-only events and ozone pollution-

only events) due to climate change. Multi-model mean changes are shown. In **(A)** and **(B)**, no overlay indicates regions where at least 80% of the models agree on the sign of the change; diagonal lines indicate opposite regions. In **(C)** and **(D)**, the error bars represent the range (uncertainty) across models. CHN: China; BTH: Beijing-Tianjin-Hebei region; YRD: Yangtze River Delta; FWP: Fenwei Plain.

pollution episodes. For summer ozone in China, the 50th percentile increases by 10% and the 95th percentile increases by 17% on heatwave days compared to non-heatwave days (Fig. S6). The enhancement effect of temperature extremes on ozone is further highlighted in polluted regions, for example, in the BTH region and the YRD region, the 50th and 95th percentiles increase by 15%–23% and 21%–27%, respectively. In the BTH region, more than 60% heatwave days are accompanied by ozone pollution events (Fig. S7). During heatwave days, favorable meteorological conditions (e.g., high air temperatures and strong solar radiation) and heightened precursor emissions (e.g., biogenic emissions) promote ozone production by accelerating photochemical reaction, which, together with the suppression of dry deposition from reduced vegetation stomatal uptake, results in an increase in accumulated ozone in the atmosphere^{6,8,34}. Therefore, the intensified heatwaves tend to occur alongside ozone extremes, particularly in heavily populated eastern metropolitan areas.

For a more detailed analysis of single and concurrent events, we further divided heatwave and ozone extremes into heatwave-only, ozone pollution-only, and heatwave-ozone compound events. As the climate warms under the SSP3-7.0 scenario, heatwave-only, ozone pollution-only, and compound events in China are projected to increase by 10 (2–15), 6 (3–10), and 6 (3–8) days per year, respectively (Fig. 2A, C). Notably, the compound-event exposure in China expands by a factor of 2 (208%; 85%–338%), much higher than the growth rates of single extreme events (135% for heatwave-only events and 33% for ozone pollution-only events). The patterns of changes in extreme events exhibit distinct regional characteristics (Fig. S8). Hot spots of compound extreme increases are projected in the North China Plain (Fig. 2A). In the BTH region, compound events are projected to increase by up to 11 days per year, dominating the rise in the three types of heat and

ozone extremes, and accounting for half of the total increase in extreme days under SSP3-7.0 (Fig. 2C). Under the SSP1-2.6 scenario, as the climate warms, the number of compound-event days and heatwave-only days both increase by ~80% compared to historical period, together with minimal change in ozone pollution-only days (Fig. 2B, D).

Based on China's ambient air quality standards, we further identify ozone pollution episodes with three different pollution levels (i.e., mild, moderate and severe pollution; see “Methods” section for definitions), and assess the climate-driven change in ozone pollution episodes and the contribution of heatwave-ozone compound events (Fig. 3). Under the SSP3-7.0 scenario, the frequency of ozone pollution events across China would increase by 13 days per year, half of which are heatwave-ozone compound events. As a population-dense region suffering from severe pollution, BTH shows the most notable rise in high levels of ozone pollution, with the moderate pollution event increasing by 9 days and severe pollution event by 4 days per year, and compound-event days make up half of the increase (Fig. 3A). This feature is also applicable to the YRD and the FWP region. As the climate warms in the future, the share of compound extremes in ozone pollution events rises markedly (Fig. 3B). Compound extreme events currently account for 13% of the mild ozone pollution events throughout the nation annually, which rises up to 25% as climate changes under SSP3-7.0. Notably, the share of compound extremes in moderate and severe pollution days amplifies from 20% in the historical period to ~40% by 2060 under SSP3-7.0. Turning to summer, the proportion of heatwave-ozone compound extremes is likely to further rise with future global warming. Under the SSP1-2.6 scenario, the number of ozone pollution episodes is projected to increase slightly by about 2 days, and compound-event days make a dominant contribution to the increase.

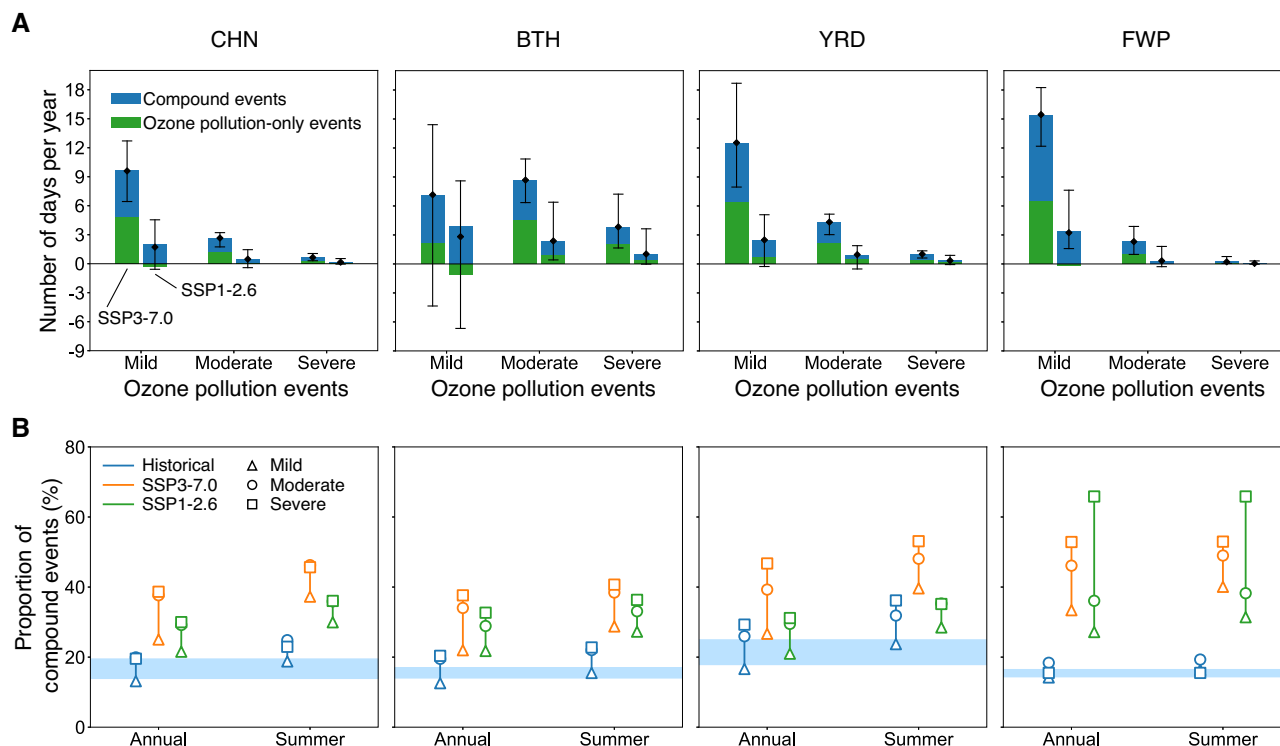


Fig. 3 | The contribution of heatwave-ozone compound events to ozone pollution in China and three key regions. A Projected changes in the frequency of ozone pollution events at different levels due to future climate change, distinguishing between heatwave-ozone compound events and ozone pollution-only events. **B** The proportion of heatwave-ozone compound events relative to different levels of ozone

pollution events on annual and summer scales during the historical period and the future period. Multi-model averages are shown. In (A), the error bars represent the range (uncertainty) across models. In (B), the blue bands indicate the proportion of compound events relative to the total number of ozone pollution events on annual and summer scales during the historical period.

Amplified health effects from heatwaves and ozone extremes

Exacerbated heatwaves and ozone extremes in a warming climate pose a serious threat to public health. Under the SSP3-7.0 scenario, more frequent concurrent heatwave and ozone pollution events due to climate change would result in 61,600 (29,900–80,600) additional deaths, exceeding the health impacts of more heatwave-only events (55,300; 9700–81,600 additional deaths) or more ozone pollution-only events (15,600; 4800–24,700 additional deaths) (Fig. 4A and Table S2). The excess deaths attributed to heatwave-ozone compound extreme events under SSP3-7.0 rise to more than three times the historical baseline. Thus, high-impact compound extremes act as the primary contributor to elevated health risks under SSP3-7.0, responsible for 46% of the overall additional mortality from intensified heat and ozone extremes due to climate change. The spatial distribution of the health impacts of compound extreme events highlights densely populated and already heavily polluted regions (Fig. S9). Of the additional mortality from more compound extremes, roughly 43% is projected to occur in BTH, YRD, and FWP, yet these three regions account for only 28% of the nation's population. In these highly polluted areas, compound extreme events outweigh single events (heatwave-only events and ozone pollution-only events) by contributing more than half of the overall additional mortality associated with more heat and ozone extremes (Fig. 4A). Under the SSP1-2.6 scenario, the additional mortality resulting from climate warming is much smaller relative to SSP3-7.0, with 22,000 (3700–44,100) additional deaths nationally due to increased exposures to compound extreme events (Fig. 4B and Table S2). Heatwave-only events, with an additional 32,900 deaths, are the primary contributor to elevated health risks under SSP1-2.6.

Epidemiological studies find that concurrent exposure to ozone pollution and heatwaves imposes a larger threat to health burden than ozone pollution-only and heatwave-only events¹³. We further decompose the factors affecting compound-event-related deaths into heatwaves, ozone, and amplification effects due to interaction (see

“Methods” section). Of the additional mortality associated with compound extreme events, heatwaves are the main contributor, while amplification effects account for roughly 17% (Fig. 4C, D). When considering both heatwave and ozone pollution events, along with their compound effects, the number of total related deaths attributed to climate warming is about 50% higher compared to estimated excess deaths that solely focus on heatwaves under the SSP3-7.0 scenario (Fig. 4A, C). This combined health impact is particularly prominent in the BTH area, reaching 1.5 times higher than the number projected based on heatwaves alone. Although the composite health risk is somewhat alleviated in the SSP1-2.6 scenario (Fig. 4B, D), it still leads to a 21% increase nationally relative to the direct extreme heat effect.

Discussion

Our study reveals for the first time the impacts of future climate change on health risks associated with heatwave-ozone compound extreme events in China. We find that, under the high greenhouse gas scenario SSP3-7.0, climate change is likely to lead to significant increases in heatwave-ozone compound events and elevated health burdens in China. Notably, in the densely populated and already heavily polluted regions, compound extreme events outweigh single events by contributing more than half of the overall additional mortality associated with more heat and ozone extremes. In the BTH area, when both heatwave and ozone pollution and the compound events are considered, the number of total related deaths attributed to climate warming is 1.5 times higher compared to estimated deaths that solely focus on heatwaves. Without stringent mitigation policies, people would suffer from the dual adverse health effects of heat and ozone simultaneously. Such high-impact compound extreme events pose a great challenge to the management of the atmospheric environment and public health in the context of climate change. The adverse health risks of compound extremes can be alleviated under the low greenhouse gas scenario with ambitious climate actions.

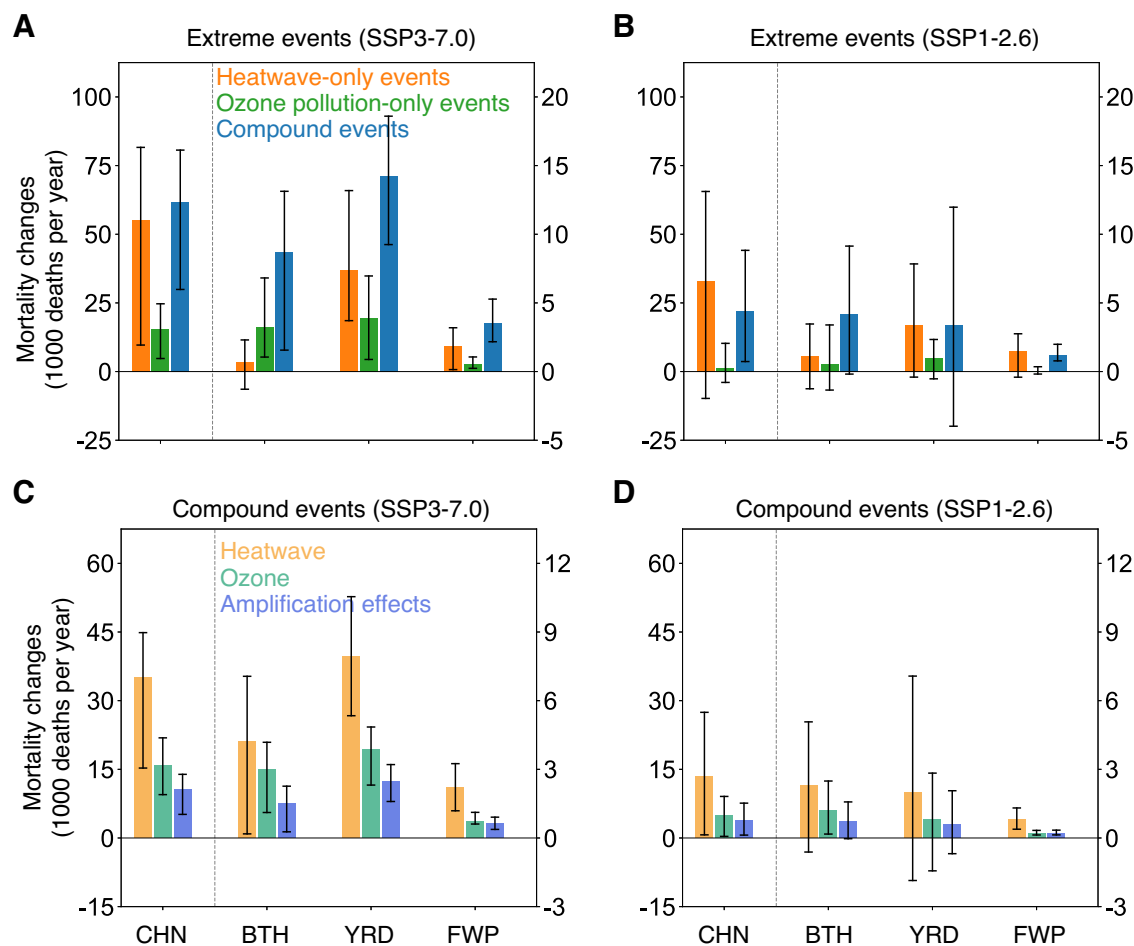


Fig. 4 | Future changes in mortality attributable to extreme events due to climate change in China and three key regions. A, B Projected changes in excess deaths attributable to two single extreme events and compound events due to climate change under the SSP3-7.0 scenario and the SSP1-2.6 scenario in the future period (2056–2060) relative to the historical period (2010–2014). C, D Projected changes in excess deaths attributable to compound events due to future climate change, where

the contributing factors to compound-related mortalities are decomposed into heatwaves, ozone, and amplification effects due to interaction. Multi-model averages are shown. The error bars represent the range (uncertainty) across models. The left Y-axis represents the nationwide mortality magnitudes, while the right Y-axis indicates the ranges across three regions.

Previous studies have found that future climate change is likely to lead to worsening ozone pollution in China^{22,23}, which is consistent with our study. Our work goes beyond previous studies by systematically examining the co-occurrence of future heatwave and ozone pollution events to reveal the excess deaths associated with heatwave-ozone compound events due to climate change. Among the health impacts triggered by climatic extreme events, we found that pollution-related indirect impacts were comparable in order of magnitude to the direct impacts of heatwaves, suggesting that both direct and indirect impacts should be included when evaluating climate-associated health impacts. The methodology of this study is also applicable to other regions of the globe. In particular, we find that heatwave-ozone compound extremes under global warming are expected to increase substantially in China. This finding may also be applicable to other polluted regions. Currently, many regions of the world, including developed countries, are still suffering from ozone pollution, and global warming would bring challenges of exacerbated heatwave-ozone compound extremes.

To deal with the high-impact compound extreme events and the health risks they pose, climate and air quality managers and public health officials should collaborate and develop response strategies. Establishing an early warning system for heatwave-ozone compound extreme events can help governments and the public adopt appropriate adaptation measures to reduce associated health risks. While we have emphasized the challenges in the future, synergies in multiple areas will bring benefits in terms of climate, air quality, and health. Climate mitigation policies, such as carbon

neutrality, can limit global warming and thus reduce the frequency of such compound events, resulting in multiple benefits for climate, air quality, and public health. In addition, climate policies targeting greenhouse gas mitigation may simultaneously reduce air pollutants and thus generate air quality co-benefits. In turn, reducing ozone pollution by abating air pollutants will not only directly reduce the frequency of ozone pollution events but also weaken the warming effect of tropospheric ozone, which is conducive to reducing the occurrence of heatwaves and compound events.

Our work is subject to several uncertainties and limitations. Firstly, there is uncertainty in projecting the impacts of future climate change on ozone pollution. Our results, grounded in multi-model ensembles, exhibit good consistency in the climate penalty on ozone and human health (Figs. S4 and S10). Secondly, we consider solely how variations in exposure to extreme temperature and ozone events resulting from climate change affect mortality. Our estimates assume that population size, age distribution, and baseline mortality rate remain unchanged. Thirdly, the exposure-response functions used for estimating health impacts of extreme events have uncertainties. Excess deaths of heatwave-ozone compound events are projected by the risk function derived from a recent epidemiological study in China¹³. Such epidemiological studies are relatively limited currently, and the greater risk when exposed to both extremes still requires further exploration. Fourthly, given the complexity and high computational cost of the multi-scenario, multi-model, high-resolution regional climate and air quality modeling framework, we employ 5-year simulation periods for both

the historical baseline and future scenarios. Longer time windows would help better characterize long-term climate impacts and variability. Beyond the projected aggravation of heatwave-ozone extremes under climate warming, heatwave-aerosol interactions also deserve further investigation^{35–38}. Compound extremes involving heatwave and aerosol, or even co-occurring heatwave, ozone, and aerosol pollution, may exacerbate short-term health burden and merit further attention.

Nonetheless, our study demonstrates that future climate warming exacerbates the occurrence of heatwaves and ozone pollution events, together with the substantial rise in the concurrent compound events involving dual impacts. Projected future mortality attributable to these extremes increases significantly throughout China, and the health burden increment from compound events holds a predominant role under the high greenhouse gas scenario. Our findings highlight the urgent need for implementing strict measures to mitigate climate change and strengthen the response mechanism to tackle concurrent compound extreme risks.

Methods

Modeling system and simulation design

A regional climate and air quality coupled modeling system driven by dynamically downscaled multi-model ensembles is established in this work to assess future climate change and its impacts on air quality in China. The dynamic downscaling methodology effectively integrates global models capable of projecting large-scale climate change with regional models that better characterize local features. Such a technique has been widely used in regional climate change projection, with more actual descriptions of terrain, surface vegetation cover, mesoscale weather systems, and extreme weather³⁹. Five global climate/climate-chemistry models from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are selected for dynamical downscaling, including CESM2, GISS-E2-1-G, MPI-ESM1-2-HR, CMCC-ESM2-SR5, and NorESM2-MM^{40–44}, based on the availability of key meteorological and chemical variables, scenario coverage, climate sensitivity range, and prior model evaluation. An overview of the detailed configurations for the five CMIP6 models is provided in Table S3. We construct meteorological downscaling interfaces of multi-model ensembles. The global large-scale driving fields are converted into intermediate format files at six-hourly intervals and interpolated onto the desired simulation domains to generate meteorological initial conditions/boundary conditions for regional modeling. Subsequently, we use the downscaled fields to drive the WRF-Chem v3.9.1 model to simulate regional climate and air quality. The regional simulations are conducted at a spatial resolution of 36 km covering the whole mainland of China, and part of East Asia and Southeast Asia. There are 24 vertical layers ranging from the surface to 100 hPa. The detailed configuration and physical/chemical parameterization schemes chosen in this study are summarized in Table S4.

This study consists of several sets of simulations (Table S5): short-term air quality simulation (2014), current simulation (2010–2014), future SSP1-2.6 scenario simulation (2056–2060), and future SSP3-7.0 scenario simulation (2056–2060). The short-term simulation, driven by the National Centers for Environmental Prediction (NCEP) Final Operational Analysis (FNL) data, aims to assess the performance of the regional model. It effectively captures the temporal variations of ozone at both national and regional scales (Fig. S11) when compared to the observational data from the China National Environmental Monitoring Center (CNEMC). The current year simulations are conducted for five years (2010–2014), with the climate fields obtained from five global model downscaling datasets during the historical period. The simulated ozone concentrations in current years driven by multi-model downscaled ensembles are compared with those driven by FNL reanalysis data, and show good performance at the monthly and daily scales (Figs. S12 and S13). In summary, the established modeling system reasonably reproduces current states and can serve to predict future changes in climate and ozone concentrations.

For future climate simulations, we selected two scenarios: SSP3-7.0, representing a high greenhouse gas and radiative forcing scenario; and SSP1-2.6, representing a sustainable and green pathway that closely

aligns with China's carbon neutrality target for 2060²⁸. The future climate simulations are conducted on a five-year scale from 2056 to 2060. The climate fields are obtained from the downscaling outputs from five individual global models under SSP1-2.6 and SSP3-7.0 scenarios, while the air pollutant emission levels and chemical boundary conditions remain unchanged. Greenhouse gas concentrations in the radiation and chemical schemes are adjusted accordingly^{33,45}. Climate changes and their effects on air quality in China are estimated through the differences between the future simulation results and the current simulation results.

Extreme event assessment

Currently, there is no unified definition of heatwave events. Previous studies have used either daily maximum temperature or daily mean temperature as the heatwave criteria, with thresholds being determined using absolute or relative metrics^{12,46}. In light of China's extensive latitudinal range and diverse regional climatology, combining absolute and relative thresholds is more beneficial for analyzing local extreme event changes and corresponding human health impacts. A heatwave in each grid cell is defined as the daily maximum temperature exceeding the 95th percentile of the current simulation (2010–2014) and for at least three consecutive days in this study, with a minimum threshold of 30 °C³¹.

Following ambient air quality standards in China, an ozone pollution event is identified as the daily maximum 8-h ozone (MDA8) concentration higher than 160 µg/m³. Ozone pollution is further classified into mild (160 µg/m³ < MDA8 ≤ 215 µg/m³), moderate (215 µg/m³ < MDA8 ≤ 265 µg/m³) and severe pollution (MDA8 > 265 µg/m³).

In addition, the occurrence of heatwave-ozone compound extreme events and their variations under future climate change are assessed. A compound event means that a heatwave and ozone pollution occur simultaneously. Similarly, an ozone pollution-only event indicates that ozone concentration exceeds the standard on that day without the occurrence of a heatwave, and a heatwave-only event is defined as a hot day without ozone pollution. To quantify the impacts of heatwave events on ozone concentrations and ozone pollution events, we examined the differences in ozone concentrations between the heatwave periods and non-heatwave periods within the same season. We estimate the contributions of heatwave and non-heatwave days to the frequencies of different levels of ozone pollution events.

Health impact assessment

Heatwave exposure has been found to pose higher risks of cardiovascular diseases, respiratory diseases, cardiopulmonary diseases, stroke, and chronic obstructive pulmonary diseases^{46,47}. Short-term ozone exposure can lead to increased deaths in circulatory, respiratory, urinary system, and nervous system diseases⁴⁸.

Heat-related deaths are estimated with the pooled all-cause mortality rate from a meta-analysis⁴⁷. We utilize the following equation to assess the heatwave-induced mortality:

$$M_H = P \times M_B \times (RR_H - 1) \quad (1)$$

where M_H denotes the number of deaths in a heatwave day, P is the gridded population, M_B represents the average daily baseline mortality rate (calculated by dividing the annual mortality rate by 365), and RR_H is defined as the relative risk associated with heatwave-related mortality⁴⁷. The annual number of heatwave-related deaths is calculated by multiplying the annual number of heatwave days by the expected daily number of deaths due to heat in each grid.

The excess deaths attributed to ozone short-term exposure are calculated from MDA8 concentrations. Following previous research⁹, our analysis of the ozone pollution impacts is based upon a log-linear exposure-response relationship between the daily ozone exposure and the total mortality rate, which is accessed from a recent two-stage statistical study

across China⁴⁹. The short-term ozone-related deaths in one day are estimated using the formula:

$$M_O = P \times M_B \times \frac{RR_O - 1}{RR_O} \quad (2)$$

where P is the gridded population, M_B represents the average daily baseline mortality rate, and RR_O is defined as the relative risk of the specific ozone exposure level. RR_O is set according to a nationwide study in 272 Chinese cities, which reported a 0.24% higher daily mortality associated with a 10 $\mu\text{g}/\text{m}^3$ increase in MDA8 ozone concentration⁴⁹. The daily deaths are subsequently summed up to calculate the ozone-related health impacts.

Concurrent exposure to heatwave and ozone pollution events has been found to impose a larger threat to health burden than ozone pollution-only or heatwave-only events. A recent study from 250 Chinese counties provides the overall health effect estimations of compound events from 2013 to 2020¹³. The relative mortality risk resulting from the interaction between the high temperature and ozone pollution is increased by ~5% for all-cause mortality. Therefore, the compound-event mortality is computed as follows, considering amplification effects:

$$M_C = \frac{RR_C - 1}{RR_C - RR_E} \times (M_O + M_H) \quad (3)$$

where M_C represents the deaths associated with the occurrence of the compound event, RR_C refers to the relative risk for concurrent events, and RR_E refers to the relative risk due to interaction (amplification effects)¹³. We also estimate the health impacts from heatwave-only events and ozone pollution-only events by summing up the number of deaths on days when the respective single extreme event exclusively occurs.

The gridded population data are derived from the WorldPop database from 2010 to 2014. The total number of population data is constrained to be consistent with the official figures from the National Bureau of Statistics in China. The baseline mortality rate during 2010–2014 is obtained from the Global Burden of Disease (GBD) 2019 study. We assume that population structure remains unchanged under future scenarios and death changes are responses to variations in the extreme event under the background of climate change.

Data availability

The CMIP6 model data is available from <https://aims2.llnl.gov/search/cmip6/>.

Code availability

The WRF-Chem model is open source and publicly available from <https://www2.mmm.ucar.edu/wrf/users/>.

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Author contributions

C.H. and Q.Z. conceived the study. M.C. and C.H. performed the analyses and interpreted the data. M.C., C.H. and Q.Z. led the writing with input from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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