Impacts of climate change on future air quality and human health in China

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In recent years, air pollution has caused more than 1 million deaths per year in China, making it a major focus of public health efforts. However, future climate change may exacerbate such human health impacts by increasing the frequency and duration of weather conditions that enhance air pollution exposure. Here, we use a combination of climate, air quality, and epidemiological models to assess future air pollution deaths in a changing climate under Representative Concentration Pathway 4.5 (RCP4.5). We find that, assuming pollution emissions and population are held constant at current levels, climate change would adversely affect future air quality for >85% of China's population (~55% of land area) by the middle of the century, and would increase by 3% and 4% the population-weighted average concentrations of fine particulate matter ($PM_{2.5}$) and ozone, respectively. As a result, we estimate an additional 12,100 and 8,900 Chinese (95% confidence interval: 10,300 to 13,800 and 2,300 to 14,700, respectively) will die per year from $PM_{2.5}$ and ozone exposure, respectively. The important underlying climate mechanisms are changes in extreme conditions such as atmospheric stagnation and heat waves (contributing 39% and 6%, respectively, to the increase in mortality). Additionally, greater vulnerability of China's aging population will further increase the estimated deaths from $PM_{2.5}$ and ozone in 2050 by factors of 1 and 3, respectively. Our results indicate that climate change and more intense extremes are likely to increase the risk of severe pollution events in China. Managing air quality in China in a changing climate will thus become more challenging.

climate change | air quality | health | extreme event | China

The effects of future climate change on public health are an active and growing area of research, including the direct impacts of more severe heat waves (1, 2) and decreased food security (3, 4) to less direct effects on the prevalence of infectious disease (5) and air pollution (6). In China, where more than 1 million people now die prematurely every year because of air pollution and where the frequency of extreme events and poor weather conditions is expected to increase under climate change (7–9), the possibility that climate change will exacerbate an already serious problem is especially concerning.

Yet, the few studies that have assessed future climate impacts on Chinese air quality have relied on global climate/chemistry models whose resolution is too coarse to capture localized features that lead to the extremely high concentrations of aerosols in densely populated urban areas especially harmful to human health (10, 11). Similarly, previous studies quantifying future climate-driven air quality changes have focused on assessment of mean climate diagnostics (10, 12, 13), neglecting the potentially important role of extreme weather events such as heat waves, heavy precipitation, and atmospheric stagnation on air quality, which may be important climate mechanisms leading to deadly air pollution events. Although more frequent and intense extreme weather events are projected under future climate change (7–9, 14–16), their impacts on atmospheric pollutant concentrations have not been quantified, which are the ultimate determinants of air quality and associated health outcomes (14, 17, 18). The role of climate extremes in future air quality and the associated health impacts are not well recognized and are rarely quantified. Yet, policy makers and the public are concerned not only with average air quality but also with extreme air pollution events, which may have a disproportionate effect on human health, and are thus a focus of clean air policies. Critical research questions for the scientific community are thus related to whether such extremes may change in the future as a result of climate change, and the underlying climate mechanisms that affect air quality. Our goal is thus to link together studies of how extreme weather events will change under climate change and studies focused on how climate change will affect air quality.

Here, we evaluate the implications of future climate change on air quality and human health in China using dynamically downscaled climate and air quality modeling (North Carolina State University's modified Community Earth System Model [CESM-NCSU] downscaled with the Weather Research and Forecasting-Community Multiscale Air Quality [WRF-CMAQ] model; cf. refs. 12, 17, 19, 20) combined with an epidemiological model.

Significance

More intense extreme events are projected under future climate change. However, the impacts of climate extremes on future air quality and associated health implications are not well recognized and are rarely quantified in China, with an enormous health burden from air pollution. Here, we estimate the climate-driven air pollution mortality in China and find that future climate change is likely to exacerbate air pollution mortality, largely influenced by the more intense extreme events such as stagnation events and heat waves. Our analysis provides quantitative assessments and insights regarding the links between climate extremes, future air quality, and public health, suggesting that extreme weather events may be an important mechanism by which climate change will affect air quality, and especially fine particulate matter.

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Details of our approach are provided in *Methods*. In summary, we compare climate variables and daily air quality in the years 2006 to 2010 with future climate and air quality in the years 2046 to 2050 under Representative Concentration Pathway 4.5 (RCP4.5; a scenario likely to avoid mean global warming of 3 °C relative to the preindustrial era) (21). Thus, we are able to assess both multiyear average changes between these periods as well as extreme events that occur more frequently in the modeled future. Air pollutant emissions are held constant at current levels in all model runs so that the effects of climate on pollution concentrations and mortality can be isolated.

Results

Fig. 1 shows projected changes in major meteorological variables in East Asia from current (2006–2010) to future (2046–2050) years in the downscaled RCP4.5 climate scenario. Seasonal changes in different Chinese regions (region definitions are provided in *SI Appendix*, Table S1) are also summarized in *SI Appendix*, Fig. S1. Mean surface temperature increases over all regions and in all seasons, with the greatest increases in the northeast [consistent with previous studies (10, 22); Fig. 1*A* and *SI Appendix*, Fig. S1]. Rising temperatures lead to increased evaporation and atmospheric water vapor, with projected increases in precipitation in the north and south regions (Fig. 1*B*). Circulation changes will complicate precipitation patterns at regional scales. Mean wind speeds are projected to decline slightly (e.g., $<0.1\ m \cdot s^{-1}$) over most of the regions and in all seasons (Fig. 1*C*), with similarly widespread decreases in the planetary boundary layer height, especially in winter (Fig. 1*D* and *SI Appendix*, Fig. S1). Together, these decreases in wind speed and boundary layer height indicate a more stable atmosphere in the future. Note that the slower surface winds are generally consistent with a weakening of general circulation under global warming (23).

Fig. 2 *A* and *B* shows the changes in fine particulate matter ($PM_{2.5}$) and ozone concentrations that result from East Asian climate change from 2006–2010 to 2046–2050 in RCP4.5 (holding current emissions constant). Mean annual $PM_{2.5}$ concentrations increase by up to 9 $\mu g/m^3$ on the North China Plain and in the Sichuan Basin (Fig. 2*A*), and ozone season (April to September) averages of daily 1-h maximum ozone concentrations increase by 2 to 8 parts per billion (ppb) over large areas of eastern China (Fig. 2*B*). Further, the changes in $PM_{2.5}$ and ozone concentrations are greatest in the heavily populated north and east regions of China (Fig. 2 *A* and *B*), where aerosol loadings and ozone precursor emissions have been the highest in recent years. Increases in winter $PM_{2.5}$ concentrations are both larger (e.g., increasing by 10% in the north region) and more widespread (*SI Appendix*, Fig. S2), with the exception of the south region, where changes in wind speed and planetary boundary layer height are minor (*SI Appendix*, Fig. S1) such that rising temperatures reduce nitrate, and thus $PM_{2.5}$ concentrations (*SI Appendix*, Fig. S2). $PM_{2.5}$ concentrations are also projected to decrease in some areas of the northwest region (Fig. 2*A*) due to reductions in windblown dust (*SI Appendix*, Fig. S2). Ozone concentrations are projected to decrease in areas such as the Tibetan Plateau, where precursor emissions are low and ozone destruction is accelerated by increased water vapor in the

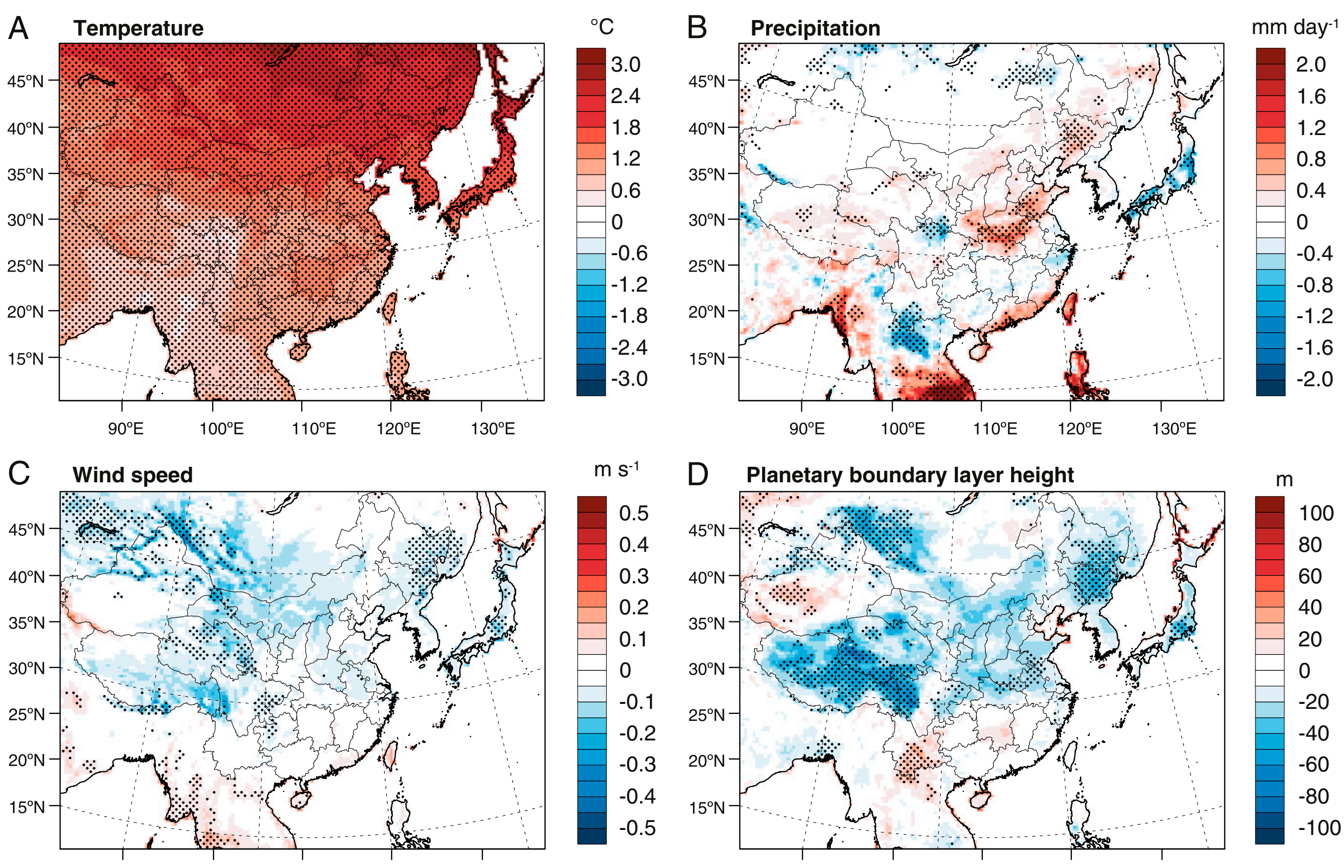

Fig. 1. Projected multiyear mean changes in major meteorological variables over East Asia. Projected mean changes in surface air temperature (*A*), precipitation (*B*), surface wind speed (*C*), and planetary boundary layer height (*D*) over East Asia are shown from current (2006 to 2010) to future (2046 to 2050) years under RCP4.5. The dots denote areas where changes are statistically significant at the 90% level, as determined by a Student's 2-sample *t* test.

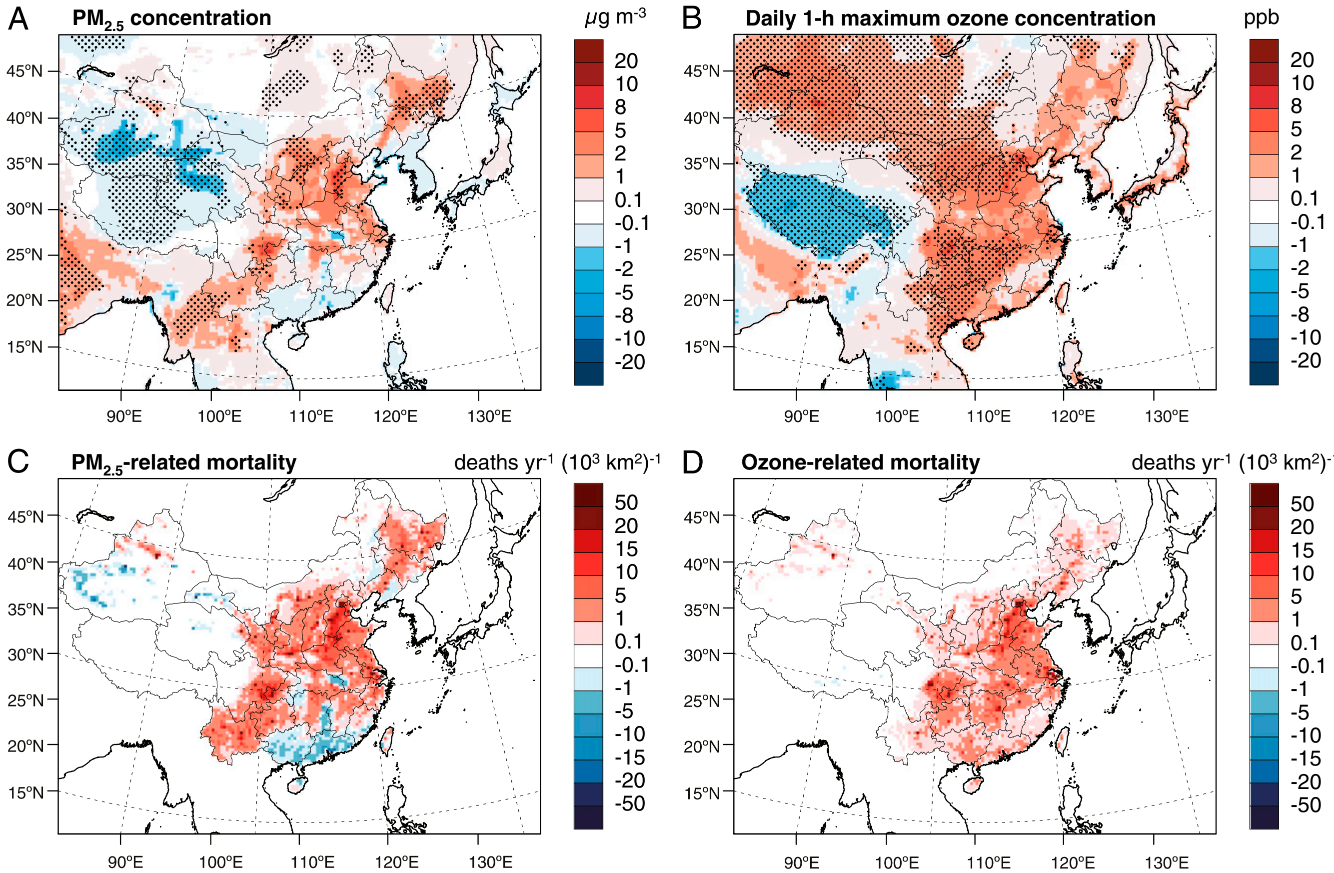

Fig. 2. Projected multiyear mean changes in air quality due to climate change and the associated health impacts in China. Projected changes in mean annual $PM_{2.5}$ concentrations (*A*) and the ozone season average of daily 1-h maximum ozone (*B*) over East Asia related to climate change under RCP4.5 are shown from current (2006 to 2010) to future (2046 to 2050) years. The estimated changes in annual mortality in China due to the climate-related changes in $PM_{2.5}$ (*C*) and ozone (*D*) exposure are shown. The dots in *A* and *B* denote areas where changes are statistically significant at the 90% level, as determined by a Student's 2-sample *t* test.

atmosphere (11). However, these improvements are exceptions; we project adverse air pollution impacts of climate change over 55% of the land area of China, areas that encompass roughly 85% of China's current population. Thus, population-weighted average $PM_{2.5}$ and ozone concentrations increase by 3% and 4%, respectively.

Fig. 2 *C* and *D* shows estimated changes in air pollution deaths due to the climate-related changes in $PM_{2.5}$ and ozone exposure. The regional distribution of these health impacts in China resembles the concentration changes, but emphasizes densely populated and already polluted areas. Indeed, although climate change increases air pollution deaths in all of the 8 regions of China, 90% of the additional deaths are projected to occur in areas that represent just 20% of China's land area, with nearly half of the additional deaths in the populous north and east regions. Although climate change is projected to decrease $PM_{2.5}$-related deaths in the south, these benefits are completely offset by ozone-related deaths in that region. Although air quality in many areas of western China is projected to improve, the health benefits are less pronounced because of the sparse population.

As previously noted, climate-related changes in air temperature, shortwave radiation, water vapor, precipitation, wind speed, planetary boundary layer height, and cloud fraction can explain some of the changes in pollution concentrations. We present further correlation analyses between changes in ozone and $PM_{2.5}$ concentrations and these meteorological variables in *SI Appendix*, *SI Text* and Fig. S3. *SI Appendix*, Fig. S3 illustrates that the increase in ozone concentrations is generally associated with the increase in temperature and the decrease in precipitation, while the increase in $PM_{2.5}$ concentrations is generally associated with the decrease in boundary layer height and wind speed. Moreover, Fig. 3 shows widespread and substantial changes in the frequency of extreme events that affect air quality from current (2006 to 2010) to future (2046 to 2050) years under RCP4.5. For example, the average frequency of heat waves across China increases from 2.7 d/y in current years to 8.8 d/y in future years (Fig. 3*A*). The increase in heavy precipitation events is less pronounced: Average frequency increases from 7.4 d/y to 8.1 d/y (Fig. 3*B*). In addition, the average frequency of atmospheric stagnation days increases from 54.0 d/y to 57.4 d/y (Fig. 3*C*). Spatial distributions of the frequency of extreme events in current and future years are shown in *SI Appendix*, Fig. S4.

In turn, we see that such climate extremes have a large influence on deadly air pollution events in the future. For example, our projections show that the number of days in 74 major cities of China with winter $PM_{2.5}$ concentrations great than 150 $\mu g/m^3$ and 250 $\mu g/m^3$ (equivalent to the heavily polluted and severe polluted levels, respectively, according to the Air Quality Index in China; ref. 24) increases by 1.8 d (11%) and 1.1 d (42%), respectively, and we find that atmospheric stagnation events account for more than 70% of these high-$PM_{2.5}$ days and dominate these increases (*SI Appendix*, Fig. S5). The reduction of surface wind speed and boundary layer height during stagnation events is unfavorable for the transport and diffusion of air pollutants, thus enhancing pollution haze (7). Similarly, the number of days in 74 major cities with summer daily 1-h maximum ozone greater than 90 ppb (approximate to the polluted level) increases by 3.8 d (12%)

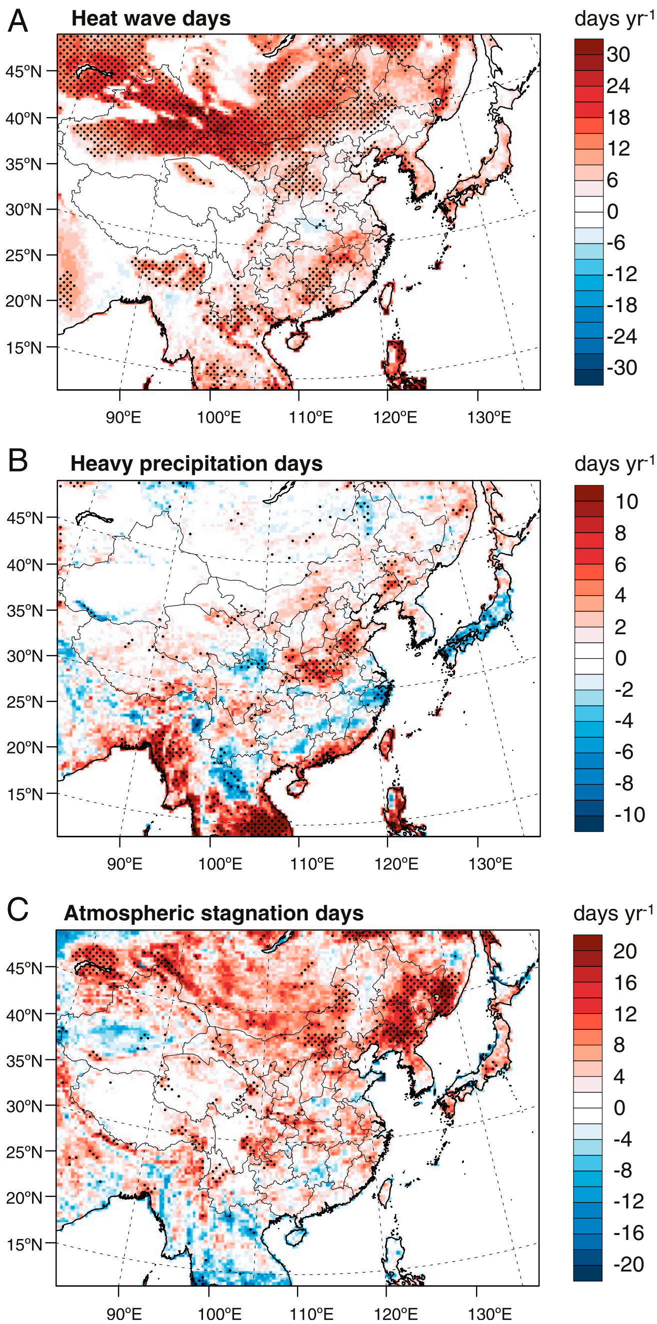

Fig. 3. Projected multiyear mean changes in the frequency of extreme events over East Asia. Projected changes in the frequency of heat wave days (*A*), heavy precipitation days (*B*), and atmospheric stagnation days (*C*) over East Asia are shown from current (2006 to 2010) to future (2046 to 2050) years under RCP4.5. The dots denote areas where changes are statistically significant at the 90% level, as determined by a Student's 2-sample *t* test.

(*SI Appendix*, Fig. S5), and about 14% of these high-ozone days occur during heat wave days as high temperatures are favorable for photochemical formation of ozone (17).

Fig. 4*A* summarizes regional changes in air pollution deaths due to climate change, showing the large fraction of deaths associated with extreme events as opposed to changes in mean climate state (excluding extremes). As can be seen, atmospheric stagnation events (dark green) represent a particularly powerful mechanism for climate-induced air pollution mortality: 39% of all additional deaths (8,100 deaths, 95% confidence interval [CI]: 6,900 to 9,300; Fig. 4*A*). Increases in heat wave events (yellow) account for 6% of all additional deaths (1,200 deaths, 95% CI: 300 to 2,000; Fig. 4*A*). In contrast, increases in heavy precipitation events (light green) act to decrease air pollution deaths somewhat in the future, especially in the north and south regions, as the precipitation increases the wet removal of aerosols and reduces the formation of ozone (Fig. 4*A*). A relatively small fraction (less than 1%) of the additional deaths are associated with compound extremes because there are very few days when different types of extreme events occur simultaneously (Fig. 4*A*).

Fig. 4*B* shows the same additional air pollution deaths due to climate change by region, but shows the causes of death. Of the additional 12,100 (95% CI: 10,300 to 13,800) $PM_{2.5}$-related deaths, 42% are related to stroke and the rest are related to ischemic heart disease (IHD), chronic obstructive pulmonary

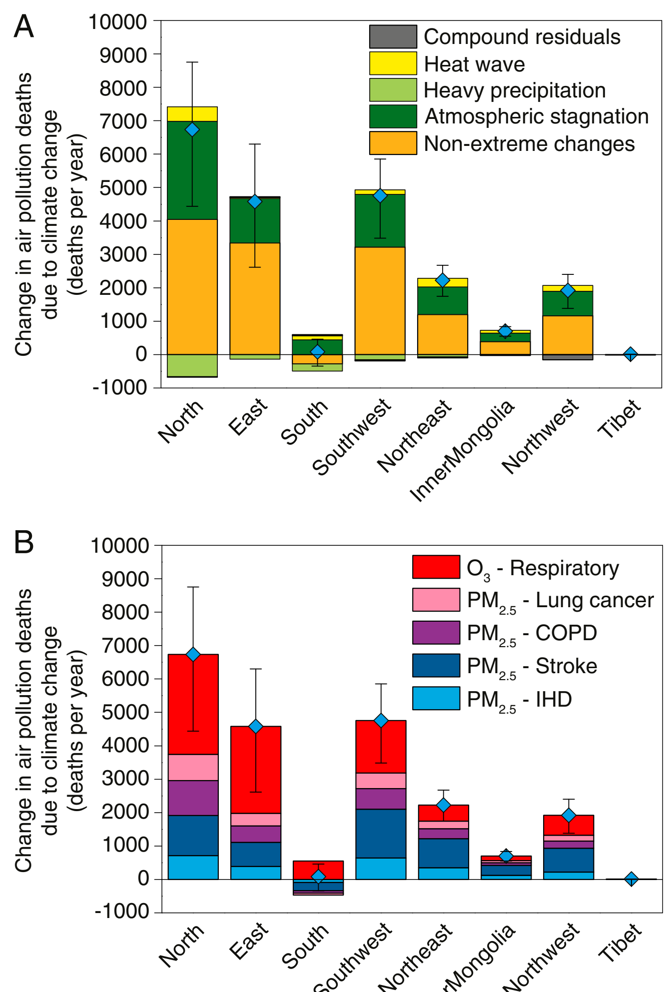

Fig. 4. Climate-induced air pollution-related mortality according to climate mechanism and cause in the 8 regions of China. Changes in air pollution deaths related to climate change under RCP4.5 are shown from current (2006 to 2010) to future (2046 to 2050) years in different regions of China, according to climate mechanism (*A*) and cause of death (*B*). The total climate-induced air pollution-related mortality is plotted as blue diamonds. Error bars denote 95% CIs, determined by uncertainties in the RRs. (*A*) Climate mechanisms are changes in mean climate state (excluding extremes, nonextreme changes), extreme-induced additional changes from heat waves, heavy precipitation, atmospheric stagnation, and the residuals due to compound extremes. (*B*) Causes are respiratory disease, lung cancer, COPD, stroke, and IHD.

disease (COPD), and lung cancer. Additional ozone-related mortality due to respiratory problems is estimated to be 8,900 (95% CI: 2,300 to 4,700) people per year.

Discussion

Our regional modeling indicates that climate change will exacerbate future air pollution mortality in China. This finding is generally consistent with previous studies despite differences in modeled time periods, scenarios, regions, climate-chemistry models used, and population and baseline mortality projections (25, 26). For example, climate change is also expected to negatively affect air quality in the United States, but compared with the United States, we project roughly an order of magnitude more climate-induced air pollution-related deaths in China (27).

Our results also go beyond previous studies in revealing the outsized role of more intense climate extremes in future climate-driven air pollution mortality in China. In total, increases in future atmospheric stagnation events contribute 68% to the climate-driven increase in $PM_{2.5}$ concentration and 39% to the increase in air pollution-related mortality (incorporating a much smaller effect on ozone concentrations) (*SI Appendix*, Fig. S6). These estimates bear out the suggestions of previous studies that increasingly frequent stagnation events could negatively impact human health (6, 14). Although less important than stagnation due to fewer event days, increases in future heat waves have a large effect on ozone concentrations, totaling 14% of the climate-driven ozone increase we project and 6% of the increase in air pollution-related mortality (*SI Appendix*, Fig. S6). In contrast, increases in future heavy precipitation events reduce 6% of the climate-driven air pollution-related mortality (*SI Appendix*, Fig. S6). Our results reveal the large effect of these climate extremes on $PM_{2.5}$ and the less pronounced effect on ozone (*SI Appendix*, Fig. S6), indicating that $PM_{2.5}$ increases dramatically under extreme conditions, while the ozone increases might be prevalent under both extreme and mean conditions due to climate warming. Given the substantial contribution from extreme weather events to the modeled increase in air pollution (especially $PM_{2.5}$) and mortality, as well as the dominant role that extreme weather events play in the increase in extreme haze events, we suggest that extreme weather events may be an important mechanism by which climate change will affect air quality, and especially $PM_{2.5}$.

Our findings here are subject to several important limitations and sources of uncertainty. First, given the high-resolution and computationally intensive methodology, our simulations are limited to a single climate-chemistry model. However, our finding that future climate change is likely to exacerbate China's air pollution is broadly consistent with numerous previous studies (8–11, 25, 26, 28, 29) that used independent models and methods. In particular, several studies have indicated that weather conditions conducive to extreme haze will likely occur at a higher frequency in China under climate change as a result of large-scale circulation changes caused by the Arctic sea ice decline and the weakening of the East Asian winter monsoon (7–9). Yet, the original air stagnation index adopted by Cai et al. (8) and Horton et al. (14) does not capture the wintertime frequent haze events in China (30). By adopting a new air stagnation index (*Methods*), we find that stagnation can identify a large fraction of severe haze events in China (*SI Appendix*, Fig. S5). The increased frequency of stagnation events is consistent with the more frequent weather conditions conducive to extreme haze as reported by previous studies (7–9). Previous studies reveal 3 potential pathways linking midlatitude weather extremes to Arctic amplification, including changes in storm tracks, the jet stream, and planetary waves (9, 31), although there is not yet consensus regarding the Arctic linkages (32). Several studies have suggested that amplified planetary waves favor weather extremes in midlatitudes (33–35).

Second, although we evaluate error in our mortality estimates related to the uncertain integrated exposure responses (i.e., uncertainty in the relative risk [RR]; details are provided in *Methods*), our projections assume no change in population size, age structure, or location. This assumption allows a direct evaluation of the effects of climate change apart from any demographic changes. However, in order to assess the potential sensitivity of our results to this assumption, we conducted further analyses using scenarios of future population and age structure. We find that greater vulnerability of China's aging population will further increase $PM_{2.5}$-related mortality and ozone-related mortality in 2050 by factors of 1 and 3, respectively (Table 1).

Thus, climate change is likely to increase air pollution mortality in China, and given demographic trends, our estimates of actual deaths may be an underestimate. The climate penalty effects on air quality and human health would be larger under a high climate scenario (e.g., RCP8.5 in 2100, which could be analyzed in future studies). They are more pronounced in densely populated and already polluted areas of China and in heavily polluted winters. Our results indicate that climate change is likely to increase the risk of severe pollution events in China, and thus alter the level of pollution control required to meet air quality targets.

This study provides quantitative assessments and important insights regarding the links between climate extremes, future air quality, and public health. Our finding that extreme weather events may be an important mechanism by which climate change will affect air quality, which provides improved understanding of the impacts as well as the underlying mechanisms, has implications for those studying climatic influence on such extreme events, for air quality modelers, and for policy makers seeking to mitigate future harms. Our results bear out the suggestion that increasingly frequent extreme events such as atmospheric stagnation and heat waves could negatively impact air quality, especially during extreme air pollution episodes. Policy makers and the public are not primarily concerned with average air quality, but with periodic episodes when air pollution is especially bad, which may have disproportionate impacts on human health, and are thus a major focus of clean air policies. For policy makers, one of the most important aspects of air quality management is therefore the mitigation of extreme air pollution episodes. If, as we find, climate change will significantly worsen such extreme

Table 1. Sensitivity analysis for climate-induced air pollution-related mortality in China

Accounting assumptions	$PM_{2.5}$-related mortality	Ozone-related mortality
Base results (current population and current baseline mortality rates)	12,100	8,900
Future population and current baseline mortality rates	43,800	40,800
Current population and future baseline mortality rates	7,200	7,400
Future population and future baseline mortality rates	27,000	35,000

The estimated air pollution-related mortality is expressed as deaths per year due to climate change under RCP4.5 from current (2006 to 2010) to future (2046 to 2050) years. The base results assume no change in population and baseline mortality rates. We conducted further sensitivity analyses using future population and future baseline mortality rates.

pollution episodes, and thus increase risks to public health, then clean air policies will be relatively less effective, and the level of pollution management required to meet future air quality targets will be even greater than what may now be anticipated. In this way, the interests of regional air quality managers and public health officials are closely aligned with efforts to mitigate climate change, because doing so will avoid climate effects on air quality, especially climate-driven increases in extreme events. The extreme diagnostics we calculate and report, which have not been a focus of previous studies, may therefore be valuable to policy makers and the public, and may be a worthwhile area for further research. The results and methodology reported here may be used in other regional or global studies to comprehensively improve the understanding of air quality and health impacts of climate change and extreme events, and they may also be applied in the investigation of the climate mechanism driving air quality change. For Chinese policy makers working to improve current air quality and protect public health, our finding is a daunting conclusion, and one that underscores the need to tackle the challenges of both climate change mitigation and air quality at the same time.

Materials and Methods

Modeling System and Simulation Design. Future climate change and its impacts on air quality in China are estimated from numerical simulations with a regional coupled climate-chemistry modeling system established using the dynamical downscaling technique. The description of the modeling system is detailed in a previous paper (36). In the modeling system, the regional 2-way coupled WRF-CMAQ model with aerosol direct effects is used to dynamically downscale the global climate from the CESM-NCSU (37–43) for a high-resolution regional climate and air quality simulation under a changing climate. The dynamical downscaling technique takes full advantage of global climate-chemistry models that can accurately predict large-scale global changes and regional models that can better represent regional phenomena. The current year simulations of the CESM-NCSU and WRF-CMAQ have been evaluated against observations to validate the model's simulation of global (41) and regional (36) climate and air quality. A comprehensive evaluation indicates that the CESM-NCSU provides a reasonable representation of the current global atmosphere, making it suitable for future climate simulations (41). In general, most meteorological variables are accurately simulated in the CESM-NCSU. The regional WRF-CMAQ model also performed well under the multiyear climatological application for both major meteorological variables and chemical variables and, in particular, outperformed global models in predicting the high $PM_{2.5}$ concentrations in urban areas as well as the surface ozone concentrations in China (36). Thus, it can better support a high-resolution health impact assessment. The regional WRF-CMAQ model reproduced the spatial distributions and seasonal and daily variations of $PM_{2.5}$ and ozone concentrations well (36). Comparisons of future climate changes projected by the CESM-NCSU with an ensemble of Coupled Model Intercomparison Project Phase 5 (CMIP5) (44) models are provided in *SI Appendix*, *SI Text* and Fig. S7). In summary, despite some discrepancies with CMIP5 models, the CESM-NCSU generally captures the sign and magnitude of future climate trends, thus providing a reasonable representation of future climate change.

The regional simulations were conducted for 5 current years (2006 to 2010, current climate) and 5 future years (2046 to 2050, future climate). They were driven by the CESM-NCSU downscaled climate under RCP4.5, keeping anthropogenic air pollutant emissions and boundary conditions constant at the current levels. The regional modeling system was applied in East Asia with a horizontal grid resolution of 36 km. Future climate change and its impacts on air quality in China are estimated from the difference between the future climate simulation and the current climate simulation. The future climate simulation used the same configurations as the current climate simulation except for the changing climate under RCP4.5. The RCP4.5 pathway is selected for this study because it represents a relatively medium climate scenario. The background mixing ratios of CO_2 and CH_4 are changed in the radiation scheme, from 378 parts per million (ppm) and 1,754 ppb in current years to 474 ppm and 1,840 ppb under RCP4.5 in future years, respectively, but are held fixed in the chemistry scheme at the CMAQ's default (current) levels. Natural emissions, including biogenic volatile organic compounds, windblown dust, and soil and lightning nitrogen oxides, were climate-dependent and in-line calculated within the 2-way coupled WRF-CMAQ.

Health Impact Assessment. The health impacts of air pollution are estimated as premature human mortality using epidemiological models. We estimate $PM_{2.5}$-related mortality due to 4 leading causes, including IHD, stroke, COPD, and lung cancer, and ozone-related mortality due to respiratory disease. The change in premature deaths is calculated using Eq. **1**:

$$\Delta M = M_b \times P \times AF, \quad [1]$$

where ΔM is the change in premature deaths due to $PM_{2.5}$ or ozone; M_b is the baseline cause-specific mortality rate; P is the gridded population; and AF is the attributable fraction of deaths due to $PM_{2.5}$ or ozone, defined as:

$$AF = \frac{RR - 1}{RR}, \quad [2]$$

where RR is the relative risk of cause-specific deaths due to $PM_{2.5}$ or ozone. For $PM_{2.5}$, the RRs are derived from the integrated exposure-response (IER) model (45, 46):

$$RR_i(C) = \begin{cases} 1 + \alpha_i\left(1 - e^{-\gamma_i (C - C_0)^{\delta_i}}\right), & C \geq C_0 \\ 1 & , C < C_0 \end{cases}, \quad [3]$$

where C is the annual mean $PM_{2.5}$ concentration; C_0 is the threshold concentration; and α, γ, and δ are fitted parameters of the concentration-response functions (CRFs) for a given cause i. The improved CRFs in the IER model more realistically account for health impacts at very high $PM_{2.5}$ concentrations (45, 46) than previous linear or log-linear CRFs (47), and hence are more suitable for China. For ozone, the RR is taken from studies by Jerrett et al. (48) and Anenberg et al. (47), in which every 10-ppb increase in seasonal (ozone season) average of daily 1-h maximum ozone is associated with a 4% increase in respiratory disease mortality. We follow the definition of ozone season (6 mo, April to September) used in previous studies (25, 47, 48), and do not consider the potential change in the length of the ozone season. Climate change in the future may lead to an extension of the ozone season, which will result in longer exposure to high ozone levels, and thus may increase the risk of diseases. By restricting our analysis to the 6-mo ozone season, we may therefore underestimate the health impacts of ozone in a changing climate with a longer ozone season. Further epidemiological studies are needed to evaluate that possibility. Note that our estimates of air pollution-related mortality also consider uncertainty in the RRs. For $PM_{2.5}$, we use the parameter values of Burnett et al. (45) to conduct 1,000 Monte Carlo simulations and then calculate the average and the 95% CIs. For ozone, we use the average and the 95% CIs for RR reported by Jerrett et al. (48).

The baseline mortality data in 2010 are derived from the Global Burden of Disease Study 2013 (49, 50). The gridded population data are obtained from the LandScan global population database. We primarily assume no demographic change for the mortality calculation but also include a sensitivity study (Table 1), where we assess the effect of expected demographic changes. For the sensitivity study, future population projections and age structures are obtained from the medium variant scenario of the United Nations Population Division. The baseline mortality for 2050 is projected based on the International Futures (51). The sensitivity to future population and mortality rate is intended to reflect the sensitivity to expected demographic changes.

Quantitative Method of Climate Extremes. We investigate climate extremes in future climate conditions and further evaluate their impacts on air quality. The climate extremes investigated in this study include heat waves, heavy precipitation, and atmospheric stagnation. Following previous studies (14, 16), we applied the criteria based on meteorological variables to define the occurrence of climate extreme events. Similar to Guo et al. (16), we define the occurrence of a heat wave when the daily maximum temperature exceeds the critical temperature threshold for at least 3 consecutive days during May to September. The temperature threshold is defined as the 95th percentile of the baseline period (2006 to 2010 in this study) and, regardless, not less than 30 °C. The original air stagnation index adopted by Cai et al. (8) and Horton et al. (14) is found to have failed to capture the wintertime frequent haze events in China due to a weak linkage between surface air pollution and upper air wind speed (30). Following recent studies (7, 30, 52), which include the boundary layer height to represent the strength of vertical mixing instead of the upper air wind speed, a new metric is proposed. We define the occurrence of an atmospheric stagnation event when the ventilation coefficient (the product of surface wind speed and boundary layer height in this study) within 1 d is less than 800 $m^2 \cdot s^{-1}$ and the precipitation accumulation is less than 1 $mm \cdot d^{-1}$ (7, 30, 52, 53). The new air stagnation index is able to capture 72% of winter severe haze days with $PM_{2.5}$ > 150 μg/m^3 (*SI Appendix*, Fig. S5); thus, it is effective in representing air stagnation. A heavy precipitation event is defined as when the daily precipitation exceeds 20 mm·d^{-1} (54). The intensification of future heat wave and precipitation extremes projected by this study is consistent with previous climate extreme studies over China based on the CMIP5 multimodel ensembles (16, 55). The projected increased frequency of stagnation events in this study is similar to that of a previous study using an ensemble of regional climate model simulations (7).

We use a simple statistical analysis method to quantify the contribution of climate extremes to climate-induced air pollution and its associated health impacts. The statistical analysis is conducted by replacing the pollutant concentrations in extreme event days with the average concentrations in nonextreme event days over a 90-d window (45 d before and after the extreme event day, approximately at seasonal scales). Any other extreme events in the 90-d window are also excluded to avoid contaminating the mean climate signal. We average the pollutant concentration over the nonextreme 90-d window and treat this as the mean climate component on that given extreme event day. We then subtract the mean climate component from the pollutant concentration during the extreme event and treat that as the climate extreme component. Therefore, we are able to assess the air quality without climate extremes as well as the contribution of climate extremes. Thus, total concentration changes in a changing climate can be further divided into 2 parts: changes in mean climate state (excluding extremes) and extreme-induced additional changes. The contribution of climate extremes to climate-induced air pollution-related health impacts is estimated based on the extremes' contribution to climate-induced total changes in annual (for $PM_{2.5}$) or seasonal (for ozone) mean concentrations (results are shown in *SI Appendix*, Fig. S6). We replace the pollutant concentrations in all of the extreme event days in the year with the nonextreme mean calculated over the 90-d window; thus, we are able to calculate the annual/seasonal mean concentration without extremes. We then compare the annual/seasonal mean concentration with and without extremes to get the contribution of extremes in annual or seasonal mean concentrations. We have added sensitivity studies instead using 60- and 120-d windows around the extreme event. The results show that extreme-induced mortality is relatively insensitive to the length of the window (results are shown in *SI Appendix*, Fig. S8).

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