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Weakening aerosol direct radiative effects mitigate climate penalty on Chinese air quality

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Future climate change may worsen air quality in many regions. However, evaluations of this 'climate penalty' on air quality have typically not assessed the radiative effects of changes in short-lived aerosols. Additionally, China's clean air goals will decrease pollutant emissions and aerosol loadings, with concomitant weakening of aerosol feedbacks. Here we assess how such weakened aerosol direct effects alter the estimates of air pollution and premature mortality in China attributable to mid-century climate change under Representative Concentration Pathway 4.5. We found that weakening aerosol direct effects cause boundary layer changes that facilitate diffusion. This reduces air-pollution exposure (~4% in fine particulate matter) and deaths (13,800 people per year), which largely offset the additional deaths caused by greenhouse gas-dominated warming. These results highlight the benefits of reduced pollutant emissions through weakening aerosol direct effects and underline the potential of pollution control measures to mitigate climate penalties locked in by greenhouse gas emissions.

Outdoor air pollution is a major public health concern as it accounts for more than three million global premature human deaths per year in recent years, more than one million of which occurred in China[1–3]. A number of previous studies have, therefore, investigated how future climate change may affect air quality and human health and found that greenhouse gas (GHG)-dominated global climate change is likely to exacerbate air pollution in most areas and thereby harm human health—a 'climate penalty'[4–11]. However, such studies typically relied on climate models or climate–chemistry models that either do not include or do not isolate the climate effects of changing short-lived climate pollutants (for example, aerosols) as future pollutant emissions also change.

Yet aerosols can strongly influence the regional and local climate by scattering or absorbing incoming radiation (that is, aerosol direct effects (ADEs)), as well as via their role in cloud formation (that is, aerosol indirect effects (AIEs)). Although previous work explored the impacts of aerosols on local climate (for example, air temperature, radiative forcing, circulation patterns and weather conditions)[12,13], few have assessed how these climate impacts may in turn affect air quality and they are generally limited to present-day impacts[14–17]. In particular, the relative importance of the regional effects of aerosols as compared with the GHG-dominated global-scale climate change effects on changes in air quality attributable to future climate change are not yet adequately quantified and thus remain unclear. For example, previous research has tended to examine the impact of future climate change on air quality by holding pollutant emissions constant or by using offline climate–chemistry models that neglect the potential climate impacts of changing aerosol feedbacks.

The climate-related impacts of aerosols could be particularly important in China, however, where current aerosol loadings are extremely high and ambitious clean air goals are expected to dramatically decrease aerosol loadings in the near future[18,19], with concomitant weakening of aerosol feedbacks as emissions of aerosol precursors are reduced. Here we assess the implications of regional climate change due to weakening ADEs for air quality and human health in China from 2010 to 2050 under Representative Concentration Pathway 4.5 (RCP4.5), a medium stabilization scenario[20], and compare the magnitude of these regional aerosol effects with those of global-scale climate change. Details of our approach and the simulation design are provided in Methods. In summary, we establish a regional coupled climate–chemistry modelling system with ADEs using a dynamical downscaling technique to assess regional climate change, air quality and their interactions within one modelling framework. By incorporating climate–chemistry interactions into regional climate projections, the simulated regional climate and air quality are jointly influenced by global-scale change derived from a global Earth system model (mainly associated with global emissions of long-lived GHG) and regional air-pollutant emissions (and the associated direct radiative effects of aerosols—ADEs). Thus, we are able to evaluate changes in ADEs as regional air-pollutant emission decline through 2010–2050 in simulations with and without aerosol feedbacks, as well as the impacts of global-scale climate change from simulations that hold regional pollutant emissions constant (see Methods for details). The associated health impacts are then estimated using epidemiological models.

Results

Under RCP4.5, the population-weighted average fine particulate matter under 2.5 μm ($PM_{2.5}$) concentration in China is projected to decrease by ~43 $\mu g\, m^{-3}$ (that is, by ~70%) from 2010 to 2050 (Extended Data Fig. 1) as it benefits from a substantial reduction in anthropogenic air-pollutant emissions (Extended Data Fig. 2 and Supplementary Table 1). A lower aerosol loading causes a weakening of ADEs in the future compared with current conditions, which in turn affects the regional climate. Figure 1a,c,e shows regional climate change in our simulations that is caused by a regional

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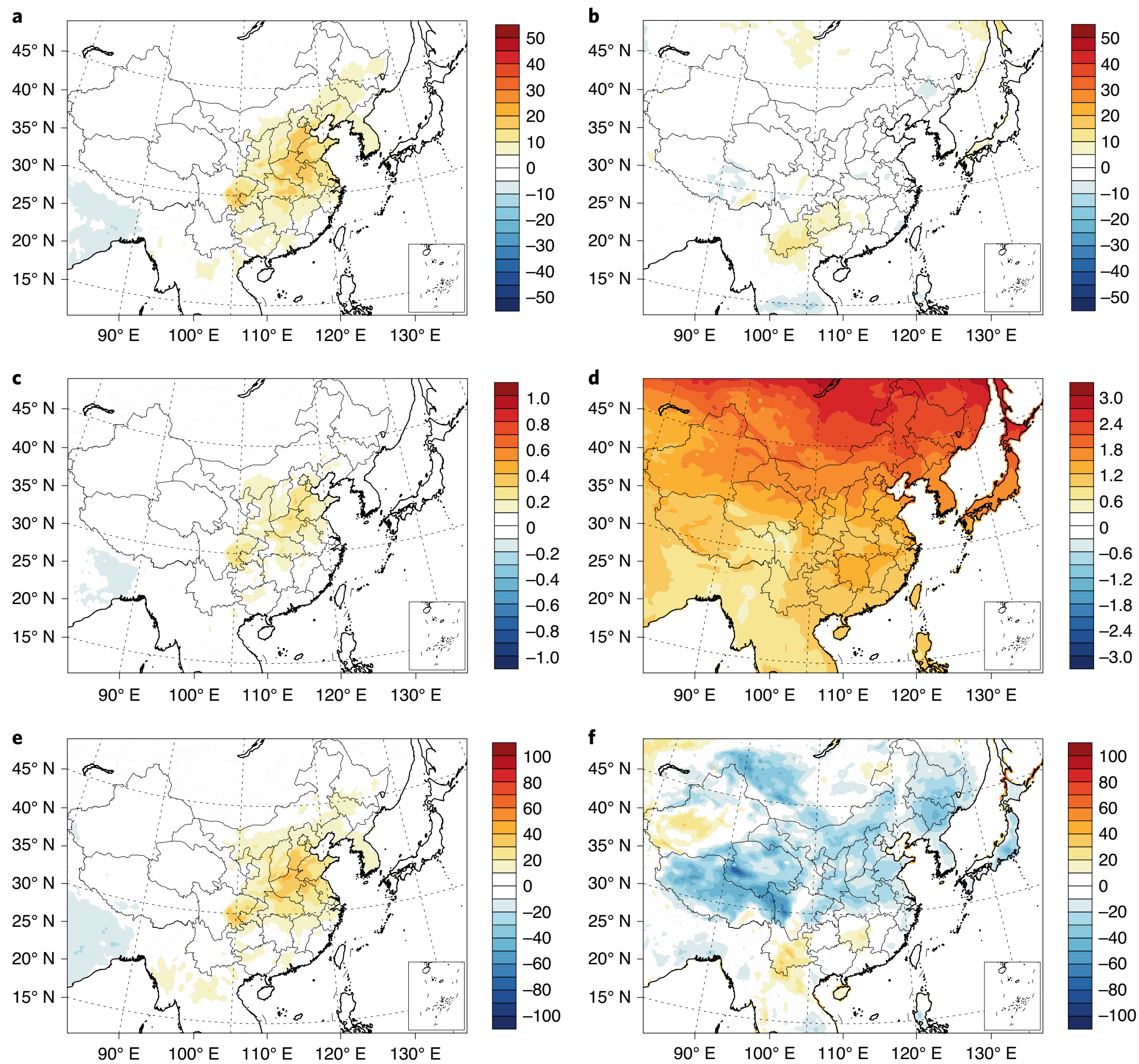

Fig. 1 | Comparison of regional climate change caused by air-pollutant-emission reduction and global-scale change. a–f, Projected annual mean changes in downward shortwave radiation at the surface (W m^{-2}) (**a**,**b**), near-surface air temperature at 2 m (°C) (**c**,**d**) and planetary boundary layer height (m) (**e**,**f**) over East Asia, caused by regional air-pollutant-emission reduction (**a**,**c**,**e**, ΔRegEmisChg, due to changing and/or weakening ADEs) and global-scale climate change (**b**,**d**,**f**, ΔGlobalClimChg) from 2010 to 2050 under RCP4.5. Insets: South China Sea.

air-pollutant-emission reduction over the period 2010–2050. This regional climate change is dominated by the weakening of ADEs between 2010 and 2050, as confirmed by the results from the feedback and no-feedback simulations (Extended Data Fig. 3; see Methods for details).

The weakening of ADEs over the period 2010–2050 reduces aerosol light extinction (both by scattering and absorption), which leads to a substantial increase of 10 W m^{-2} in population-weighted average downward shortwave radiation at the surface in China (Fig. 1a), which in turn overwhelms the minor change caused by global-scale climate change during the same period (Fig. 1b; the impacts of global-scale climate change are discussed in Hong et al.[6]). Weakening ADEs also lead to an increase in average near-surface (2 m) air temperature of 0.13 °C in China (Fig. 1c)—in addition to the GHG-dominated global-scale warming under RCP4.5 (1.3 °C; Fig. 1d). Weakening ADEs also weaken the temperature inversion during haze episodes and cause a more unstable boundary layer, mainly through two mechanisms: the increase in solar radiation leads to a near-surface temperature increase, and fewer light-absorption particles (such as black carbon) weaken the warming in the upper boundary layer[14,15,17]. As a result, the average planetary boundary layer height increases by 19 m in China (Fig. 1e), which largely offsets the decreases caused by global-scale climate change (~13 m; Fig. 1f). As shown in Fig. 1a.c.e, weakening ADEs increase downward shortwave radiation, near-surface temperatures and the boundary layer height in most areas of China. Importantly, the spatial distribution of these changes resembles the concentration decreases under RCP4.5 (Extended Data Fig. 1)—the greatest changes occur in heavily polluted areas in which substantial reductions in precursor emissions and aerosol loadings are projected to cause a stronger weakening of ADEs.

Figure 2 summarizes the population-weighted average changes in regional climate and air quality over China caused by ADEs in 2010 (current) and 2050 (future), and the weakening of ADEs between 2010 and 2050 (future minus current) in comparison with those caused by regional pollutant emission reduction and global-scale climate change (see Methods for details). In 2050, ADEs over China reduce the near-surface temperatures (cooling effects), downward shortwave radiation and boundary layer height by 0.16 °C, 3.9% and 2.9%, respectively (Fig. 2b)—much smaller than the reductions

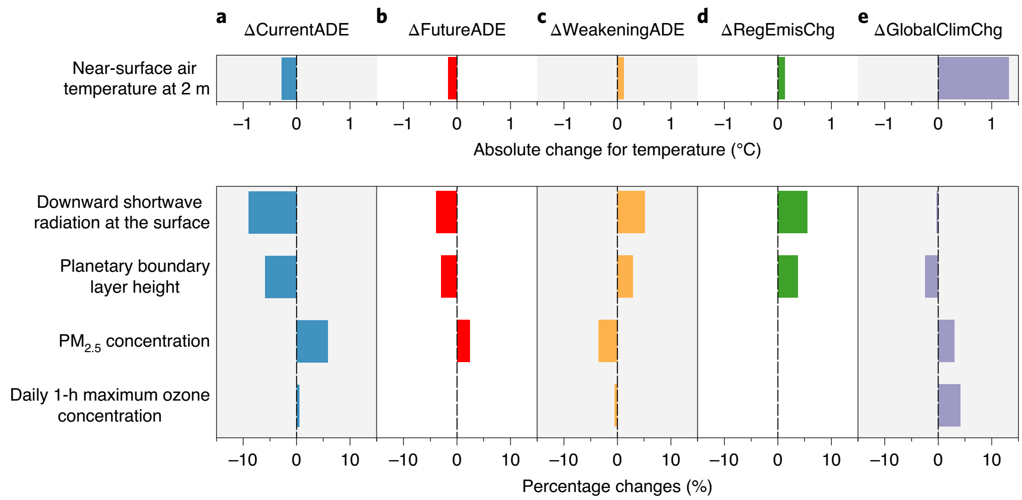

Fig. 2 | Population-weighted average changes in regional climate and air quality over China. a,**b**, Annual mean changes due to ADEs in 2010 (ΔCurrentADE) (**a**) and ADEs in 2050 (ΔFutureADE) (**b**). **c**–**e**, Projected annual mean changes due to weakening ADEs (ΔWeakeningADE) (**c**), regional air-pollutant-emission reduction (ΔRegEmisChg) (**d**) and global-scale climate change (ΔGlobalClimChg) (**e**) from 2010 to 2050 under RCP4.5. Changes in $PM_{2.5}$ and ozone concentrations due to pollutant emission reduction exceeded the axis limits and are not shown.

caused by ADEs in 2010 (0.28 °C, 9.0%, and 5.9%, respectively; Fig. 2a). In turn, the weakening of ADEs between 2010 and 2050 increases near-surface temperatures (as a result of weakened aerosol cooling effects), downward shortwave radiation and the boundary layer height by 0.12 °C, 5.1% and 2.9%, respectively, in China (Fig. 2c), in each case similar to increases caused by regional pollutant emission reduction (0.13 °C, 5.5% and 3.7%, respectively; Fig. 2d), which indicates that the weakening of ADEs is caused by air-pollutant-emission reduction. The increase in boundary layer height caused by the weakening of ADEs is more conducive to the diffusion of pollutants, and, in particular, reduces surface $PM_{2.5}$ concentrations over China by ~4% (Fig. 2c). Therefore, pollution control measures that reduce air-pollutant emissions will improve air quality not only by reducing primary and precursor emissions, but also by weakening ADEs and changing the local climate. Our results indicate that the impacts on air quality due to future climate change caused by the weakening of ADEs cannot be ignored, because they are likely to mitigate the adverse effects of global-scale climate change on air quality (Fig. 2e). However, the weakening of ADEs is mostly related to $PM_{2.5}$; the impact of weakening ADEs on average ozone concentrations in China is minor.

Figure 3 further compares the spatial distributions of changes in regional air quality attributable to two sources of climate change from 2010 to 2050: weakening ADEs and global-scale climate change. The changes in $PM_{2.5}$ caused by weakening ADEs are greatest in heavily polluted areas of China (Fig. 3a), as might be expected. In particular, weakening ADEs reduce mean annual $PM_{2.5}$ concentrations on the North China Plain and in the Sichuan Basin by up to 5 μg m^{-3} (Fig. 3a), which largely offsets the increases from global-scale climate change in these heavily polluted areas (Fig. 3b). As shown in Extended Data Fig. 4a, the $PM_{2.5}$ reductions due to the weakening of ADEs increase from 0 to more than 5 μg m^{-3} with increasing population density. Air-pollutant emissions and aerosol loadings are usually higher in urban areas in which people, vehicles and factories are concentrated. Thus, more notable benefits on human health from weakening ADEs in the future can be expected to occur in urban areas. Indeed, we found that the weakening of ADEs can largely mitigate the climate penalty on $PM_{2.5}$ from global-scale climate change in densely populated urban areas (Extended Data Fig. 4b). In contrast, weakening ADEs have either negative or positive impacts on tropospheric ozone (Fig. 3c): they may reduce ozone in the summer, but increase ozone in the winter as a result of different ozone chemistry—changes from a volatile-organic-compound-limited regime in winter to a nitrogen oxides (NO_x)-limited regime in summer across most of China[21]. The decrease in NO_x concentrations from weakening ADEs enhances the ozone level in the volatile-organic-compound-limited regime due to weakened inhibition and/or titration effects by NO_x, but it reduces the ozone level in the NO_x-limited regime due to a lower precursor level. Although weakening ADEs reduce ozone in some areas, they do not largely offset the climate penalty on ozone from global-scale climate change in most heavily polluted areas in China (Fig. 3d).

Figure 4 compares the estimated changes in air-pollution- and heat-related premature mortality in China attributable to two sources of climate change from 2010 to 2050: weakening ADEs and global-scale climate change. As can be seen, the regional distribution of these health impacts in China resembles the concentration changes (Fig. 3), but also emphasizes densely populated and already-polluted areas. Avoided $PM_{2.5}$- and ozone-related deaths in China due to weakening ADEs are estimated to be 12,600 and 1,200 people per year, respectively (95% confidence interval (CI): 9,900–15,400 and 300–2,000, respectively) (Fig. 4a,b), compared with additional deaths caused by global-scale climate change (12,100 and 10,300; 95% CI: 9,500–14,700 and 2,500–17,100, respectively) (Fig. 4d,e), which indicates that weakening ADEs play an important role in future air-pollution mortality attributable to climate change in China. In contrast, the additional heat-related deaths in China due to weakening ADEs are estimated to be 2,300 people per year (95% CI: 600–4,000) (Fig. 4c), which are compensated by the avoided $PM_{2.5}$- and ozone-related deaths and indicates that weakening ADEs have an overall beneficial effect from a health perspective.

Our simulations also show that the enhancements in annual $PM_{2.5}$ concentrations due to ADEs in 2010 increase from zero (that is, no enhancements) to more than 8%, and then approximately saturate across different areas of China as a function of increasing aerosol loadings (Fig. 5). The $PM_{2.5}$ enhancements could be as high as 6–9% in China's cities with current $PM_{2.5}$ concentrations higher than 80 μg m^{-3}. These results further support the above finding that the weakening of ADEs will have additional air-quality benefits. The non-linear relationship is also found in the aerosol–planetary boundary layer feedback[15]. This suggests that an immediate

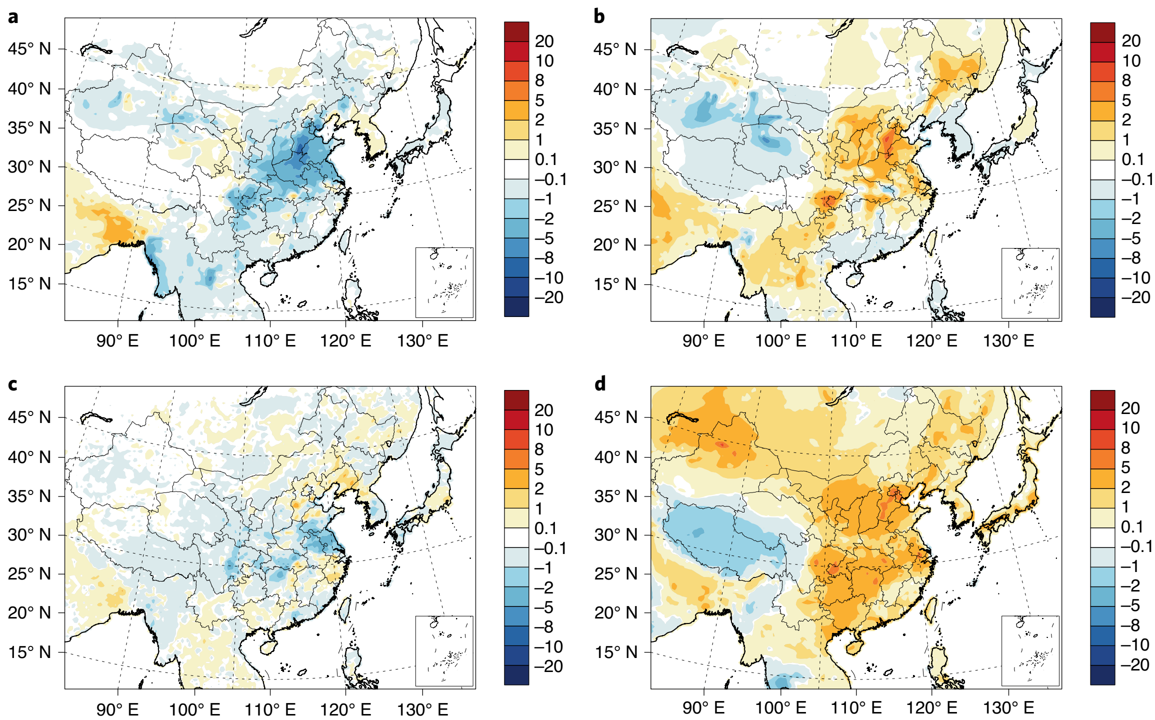

Fig. 3 | Comparisons of changes in regional air quality attributable to two sources of climate change. a–d, Projected changes in annual mean $PM_{2.5}$ concentrations ($\mu g\,m^{-3}$) (**a**,**b**), and ozone season (April–September) average (ppb) of daily 1-h maximum ozone (**c**,**d**) over East Asia caused by ΔWeakeningADE (**a**,**c**) and ΔGlobalClimChg (**b**,**d**) from 2010 to 2050 under RCP4.5. Insets: South China Sea.

benefit of air-quality improvement will be achieved when $PM_{2.5}$ concentrations are reduced down to a certain threshold (for example, $35\,\mu g\,m^{-3}$). Note that the aerosol climate effects concern not only megacities in China, but are also likely to apply to other polluted megacities in the world in which current aerosol loadings are extremely high, such as Delhi, Dhaka, Karachi, Cairo, Mumbai and Istanbul (Fig. 5). These cities will gain considerable benefits from weakening ADEs by local air-pollutant-emission reduction.

Discussion

Weakening ADEs and GHG-dominated global-scale climate change are both associated with surface warming, but they affect regional climate through different mechanisms that have opposing effects on air quality. The ADEs are mostly localized over regions with high aerosol loadings and mainly associated with the modulation of atmospheric dynamics within the boundary layer[14,15], whereas global-scale climate change mainly affects regional air quality by influencing large-scale circulation patterns[8,22]. The magnitude of ADEs is remarkably high, and the mechanisms by which they influence air quality are more robust than global-scale climate change, such that ADEs have an important effect on future climate impacts on air quality in polluted megacities in the world where current aerosol loading is extremely high.

Our results indicate that the weakening of ADEs will partly avoid the climate penalty on air-pollution mortality in China through changing regional climate. In comparison with the simulated impacts in the United States and Europe[23–25], this study shows a higher magnitude of aerosol impacts on current climate and air quality in China, which is generally consistent with previous studies over East Asia[16,17,21,26] (Supplementary Information). However, our results go beyond most previous studies in revealing the outsized role of weakening ADEs in future climate-induced air-pollution mortality in China. We estimate that weakening ADEs between 2010 and 2050 under RCP4.5 will avoid 13,800 deaths per year in China by reducing $PM_{2.5}$ and ozone exposure, roughly comparable to the increase in air-pollution deaths projected to result from global-scale climate change[6] (we estimate ~20,000 Chinese deaths per year). There have been considerable variations in estimated air-quality implications of climate change among different studies[4,5,8,22,27]. Previous studies that used offline climate–chemistry models or held constant anthropogenic pollutant emissions[4,5] neglect the potential climate impacts of weakening aerosol feedbacks caused by air-pollutant-emission reduction, whereas studies that have assessed changes in weather conditions using coupled climate–chemistry models and changing pollutant emissions[8,22] may include (but not isolate) the effects of weakening aerosol feedbacks. In particular, Horton et al.[22] projected that air stagnation over eastern China will predominantly decrease in the early twenty-first century, but then predominantly increase by the late twenty-first century. Their projections included changes in aerosol effects, which could, in part, explain their results, as weakening aerosol effects (which would tend to reduce stagnation) may dominate in the near-term and GHG-dominated global climate change (which may increase stagnation) could dominate in the long-term. Our results point to changes in aerosol effects as a potentially important source of the differences among different climate-air-quality studies and, indeed suggest caution in interpreting results from studies that do not consider the radiative effects of aerosols, especially with regard to now heavily polluted regions.

Our findings here are subject to several limitations and sources of uncertainty. First, in this study, we focused on aerosol radiative effects. AIEs on cloud properties are not included, because they remain subject to large uncertainties[28]. However, recent studies suggested that AIEs may act to increase $PM_{2.5}$ exposures in China and their impacts are less important than those of ADEs[17,29]. Further research is needed to improve the characterization of AIEs so that comprehensive assessments of aerosol climate effects can be made. Second, meteorological variability may cause uncertainties in the estimation of aerosol effects. However, future changes in $PM_{2.5}$

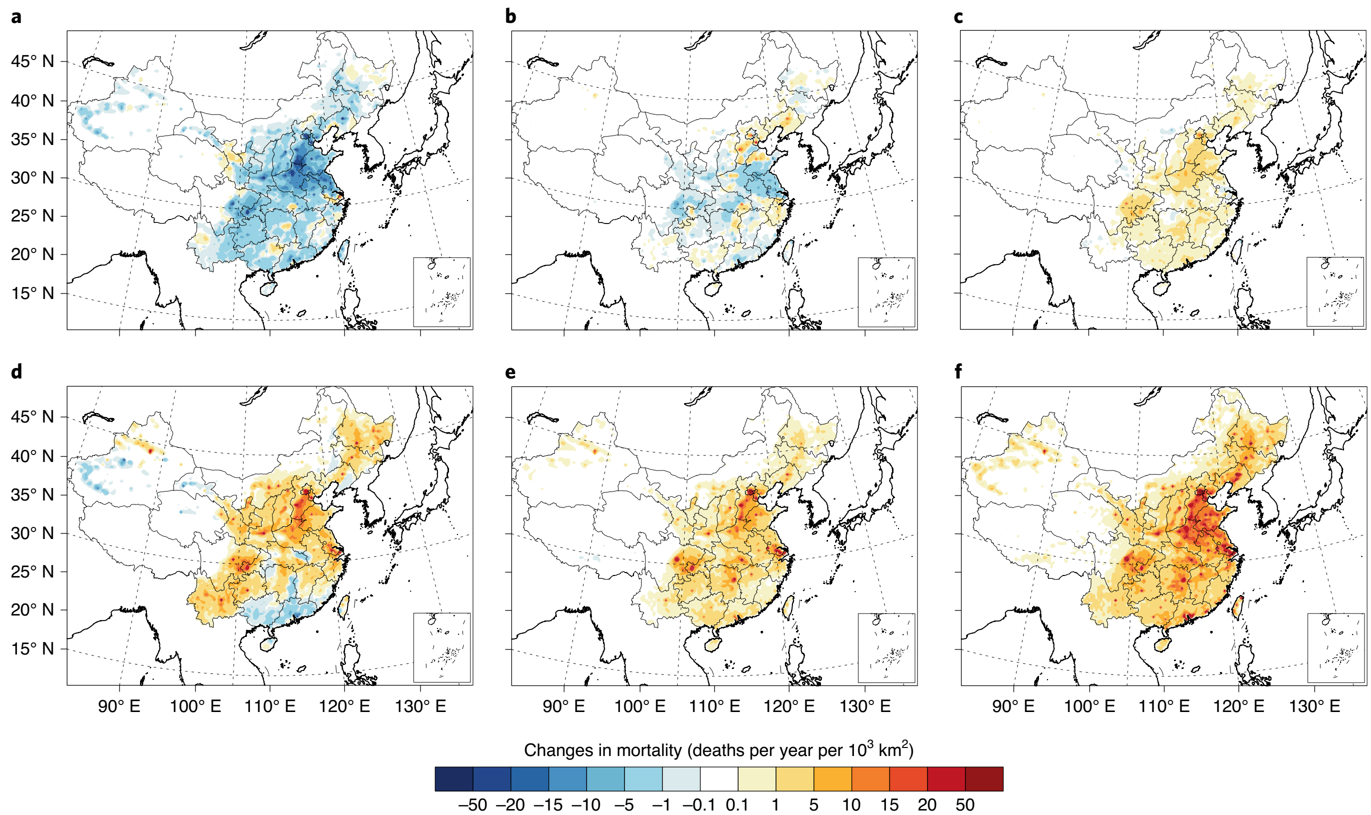

Fig. 4 | Comparisons of changes in air-pollution and heat-related mortality attributable to two sources of climate change. a–f, Estimated changes of $PM_{2.5}$-related (**a**,**d**), ozone-related (**b**,**e**) and heat-related (**c**,**f**) premature mortality in China, caused by ΔWeakeningADE (**a**–**c**) and ΔGlobalClimChg (**d**–**f**) from 2010 to 2050 under RCP4.5. Insets: South China Sea.

concentrations in polluted areas are much more sensitive to emissions than to meteorology, which lends confidence to our results regarding weakening ADEs in China. Third, although we evaluate uncertainty in our mortality estimates related to the uncertain integrated exposure responses (that is, relative risks (RRs)) and baseline mortality rates (see details in Methods), our base results assume no change in population and baseline mortality rates. This assumption allows a direct evaluation of the effects of climate change apart from any demographic changes. Further sensitivity analyses using future population (and age structure) and baseline mortality rates (Supplementary Information) suggest that a greater vulnerability of China's ageing population in 2050 will more than double the air-pollution-related avoided mortality and heat-related mortality (Supplementary Table 2). Thus, given demographic trends, we may underestimate changes in mortality. Additionally, only the impact of air pollution to human health is addressed in this study. Other impacts, such as the ozone impact on crop production, are not included. Finally, the RCP4.5 pathway selected for this study represents a relatively medium climate and air-pollution control scenario[20]. The global-scale climate penalty we observe is generally consistent with that of previous studies[5,30,31], but the penalty that arises from GHG-dominated global climate change may be larger in the long-term under a very high GHG scenario (for example, RCP8.5 in 2100)[5], and the benefits of weakened ADEs could be higher in the shorter term with more ambitious clean-air actions (for example, RCP2.6 in 2050).

International efforts to reduce GHG emissions and national efforts to reduce air-pollutant emissions are both likely to benefit human health by mitigating the climate penalty on air quality in China. However, note that the additional benefits from reducing air-pollutant emissions are mainly local and near-term due to their shorter lifetime, and hence are within a time frame relevant for national policymakers. In the short term, this is an appealing option as the regional air-pollution mitigation itself will produce immediate benefits that can help counter the potential climate penalty already

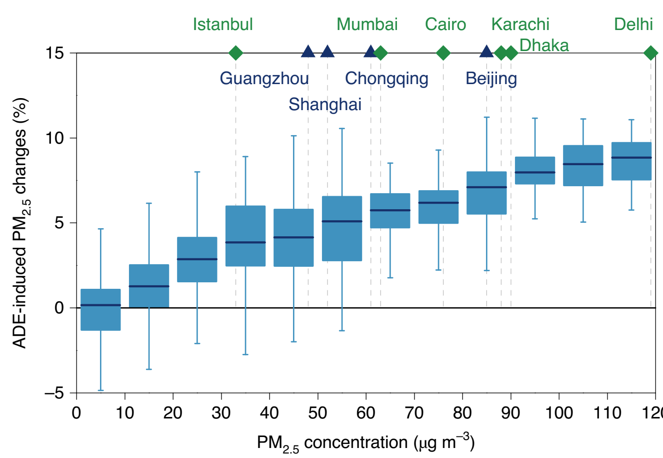

Fig. 5 | Enhancement of surface $PM_{2.5}$ concentrations due to ADEs in 2010 as a function of ambient $PM_{2.5}$ concentrations. The distribution is derived from all the grids in China (ΔCurrentADE). Blue triangles and green diamond symbols show surface $PM_{2.5}$ concentrations monitored in megacities in China and other countries, respectively (data source: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/). Box plot elements: centre line, median; box limits, upper (75th) and lower (25th) percentiles; whiskers, 1.5 times the interquartile range.

'locked in' by global GHG emissions. The Chinese government has set ambitious goals and taken actions to improve current air quality, and one may fear that future climate change may increase the level of pollution management required to meet future air-quality targets. Our results provide additional motivation to Chinese policymakers working on reducing air-pollutant emissions as it achieves direct benefits on air quality and indirect benefits from weakening ADEs and thus mitigating the climate penalty on air quality.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0840-y.

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Methods

Modelling system and simulation design. Regional climate, air quality and their interactions in China were simulated using a regional coupled climate–chemistry modelling system established with a dynamical downscaling technique. In the modelling system, the regional two-way coupled Weather Research and Forecasting–Community Multiscale Air Quality (WRF-CMAQ) model[32] with ADEs is dynamically driven by North Carolina State University's modified Community Earth System Model (hereafter CESM_NCSU)[33–39] for high-resolution simulations under a changing climate. The description and evaluation of the modelling system are detailed in a previous paper[40] (Supplementary Information). The two-way-coupled WRF-CMAQ model simulates direct aerosol radiative feedback effects by using the core–shell model to calculate aerosol optical properties and the Rapid Radiative Transfer Model for General Circulation Models radiation scheme to calculate the short-wave direct radiation effect of aerosols. Aerosol optical properties were calculated based on the simulated aerosol composition and size distribution, and then fed back to the radiation module, which in turn affects the atmospheric thermodynamic process. Such changes in meteorological conditions can further affect regional air quality. By incorporating climate–chemistry interactions into regional climate projections, the simulated regional climate is affected not only by the global large-scale climate fields derived from CESM_NCSU (mainly associated with global emissions of long-lived GHG), but also by regional air-pollutant emissions due to the presence of ADEs. AIEs on cloud properties are not included in this study due to the large uncertainties in their representation.

The simulations conducted in this study are summarized in Supplementary Table 3. The baseline regional simulations were conducted for 5 yr around 2010 (current, 2006–2010) and 2050 (future, 2046–2050) in East Asia with a horizontal grid resolution of 36 km, driven by the global large-scale climate fields from CESM_NCSU and regional air-pollutant emissions under RCP4.5[20]. The RCP4.5 pathway was selected because it represents a relatively medium climate and air-pollution control scenario. The current baseline simulation (SimCurBase) was previously evaluated against surface and satellite observations[40] (Supplementary Information). The future baseline simulation (SimFutBase) combines the effects of global climate change and regional pollutant-emission change to predict future climate and air quality under RCP4.5. In addition, a simulation of global climate change only (SimClimOnly), which uses the same configurations as the current baseline simulation except for the changing global large-scale climate fields around 2050 under RCP4.5, is conducted to assess regional climate change resulting from global-scale change and its impacts on air quality (ΔGlobalClimChg (SimClimOnly − SimFutBase); the results are presented and discussed in Hong et al.[6]). All three simulations include the effects of ADEs. The simulated regional climate differs between the future baseline simulation and the simulation of global climate change only (their configurations are different in terms of regional pollutant emissions—future and current, respectively), and the differences reflect local climate change caused by the weakening of ADEs that results from the regional pollutant-emission change (ΔRegEmisChg (SimFutBase − SimClimOnly)). Therefore, regional emission reduction has direct impacts on air quality through reducing primary and precursor emissions and indirect impacts on air quality through changes in local climate by weakening ADEs. However, air-quality changes caused by ΔRegEmisChg are dominated by the direct impacts from changes in emissions themselves, rather than the indirect impacts from local climate change, and thus cannot exactly reflect the additional changes in air quality caused by weakening ADEs.

Therefore, two additional sensitivity simulations, in which aerosol feedbacks (ADEs here) are turned off, were conducted for 2010 and 2050. By comparing the results from the feedback and no-feedback simulations, we can assess relative changes in climate and air quality caused by ADEs in 2010 (ΔCurrentADE) and ADEs in 2050 (ΔFutureADE), as well as the weakening of ADEs between 2010 and 2050 (ΔWeakeningADE (ΔFutureADE − ΔCurrentADE)). The two no-feedback simulations were conducted for 1 yr due to limited computing resources. Note that the simulated regional climate change caused by the weakening of ADEs from the feedback and no-feedback simulations (ΔWeakeningADE, 1-yr runs) is generally similar to that caused by regional pollutant emission change (ΔRegEmisChg, 5-yr runs) (Extended Data Fig. 3), which indicates that the 1-yr result well represents the 5-yr average, despite some discrepancies from interannual variability in the meteorology.

Health-impact assessment. We estimated the health impacts of air pollution and climate change as premature mortality using epidemiological models. We calculated cause-specific mortality attributable to long-term exposure to $PM_{2.5}$, ozone and temperature change, which included ischaemic heart disease, stroke, chronic obstructive pulmonary disease and lung cancer for $PM_{2.5}$ exposure, respiratory disease for ozone exposure and respiratory and cardiovascular diseases for heat exposure. The change in premature deaths (ΔM) is calculated by equation (1):

$$\Delta M = M_{\mathrm{b}} \times P \times \mathrm{AF} \tag{1}$$

where M_{b} is the cause-specific baseline mortality rate, obtained from the Global Burden of Disease Study of 2013[41,42], P is the gridded population, derived from the LandScan global population database and AF is the attributable fraction of deaths from a cause-specific disease, which is defined as:

$$\mathrm{AF} = \frac{\mathrm{RR} - 1}{\mathrm{RR}} \tag{2}$$

where RR is the relative risk for the cause-specific mortality. For $PM_{2.5}$-related mortality, the RR value is obtained from the Integrated Exposure-Response (IER) model[43,44]:

$$\mathrm{RR}(C) = \begin{cases} 1 + \alpha\left(1 - \mathrm{e}^{-\gamma(C - C_0)^{\delta}}\right) & C \geq C_0 \\ 1 & C < C_0 \end{cases} \tag{3}$$

where C is the annual mean ambient $PM_{2.5}$ concentration, C_0 is the threshold concentration and α, γ and δ are the cause-specific fitted parameters. Compared with the previous linear or log–linear concentration-response functions[45], the Integrated Exposure-Response model more realistically accounts for the impacts at very high $PM_{2.5}$ concentrations[43,44] and hence might be more suitable for China. For ozone-related mortality, we used the RR value from Jerrett et al.[46] as applied by Anenberg et al.[45] (that is, a 10 ppb increase in a 6-month ozone season average of 1-h daily maximum ozone would lead to a 4% increase in respiratory disease mortality). For heat-related mortality, the RR value was taken from Basu and Ostro[47]. For the mortality estimates, we also report uncertainties associated with the RRs and baseline mortality rates. The uncertainty ranges of baseline mortality rates were obtained from the Global Burden of Disease Study. For $PM_{2.5}$-related mortality, we used the parameter values of Burnett et al.[43] to conduct 1,000 time estimates and then calculated the average and the 95% CI. For ozone- and heat-related mortality, we used the average and the 95% CIs for RR reported by Jerrett et al.[46] and Basu and Ostro[47], respectively. Owing to the lack of regional-specific data, we used the national baseline mortality rates obtained from the Global Burden of Disease Study, which ignore the regional variability of baseline mortality rates and so introduce additional uncertainties. Developing regional-specific mortality data could improve the estimates in the future. The potential health synergies between the effects of air pollution and warming are not investigated in this study. Further epidemiological research is needed to evaluate the potential synergies.

Data availability

The RCP4.5 emissions in 2010 and 2050 are available from http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&. The demographic and epidemiological data for mortality calculation is provided in Supplementary Dataset. Source data for the main figures are available at https://github.com/ChaopengHong/Hong_et_al_2020_Aerosol. The other data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

The two-way coupled WRF-CMAQ model is open source and publicly available. The WRF version 3.4 codes can be downloaded at http://www2.mmm.ucar.edu/wrf/users/download/get_source.html. The CMAQ version 5.0.2 codes and the WRF-CMAQ two-way package can be downloaded at https://www.cmascenter.org/download.cfm. The build instructions and run instructions for the two-way coupled WRF-CMAQ model are available at https://www.airqualitymodeling.org/index.php/CMAQv5.0.2_Two-way_model_release_notes. The code to generate the main figures is available at https://github.com/ChaopengHong/Hong_et_al_2020_Aerosol. Maps used in the spatial plots were created using the NCAR Command Language (v.6.4.0; https://doi.org/10.5065/D6WD3XH5). Maps of China were updated with a database provided by https://github.com/huangynj/NCL-Chinamap.

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Author contributions

Q.Z., Y.Z. and C.H. designed the research. C.H. performed the research. Y.Z. contributed CESM simulation results and new analytical approaches. C.H., Q.Z. and S.J.D. interpreted the data. C.H., Q.Z., S.J.D. and Y.Z. wrote the paper with input from all the co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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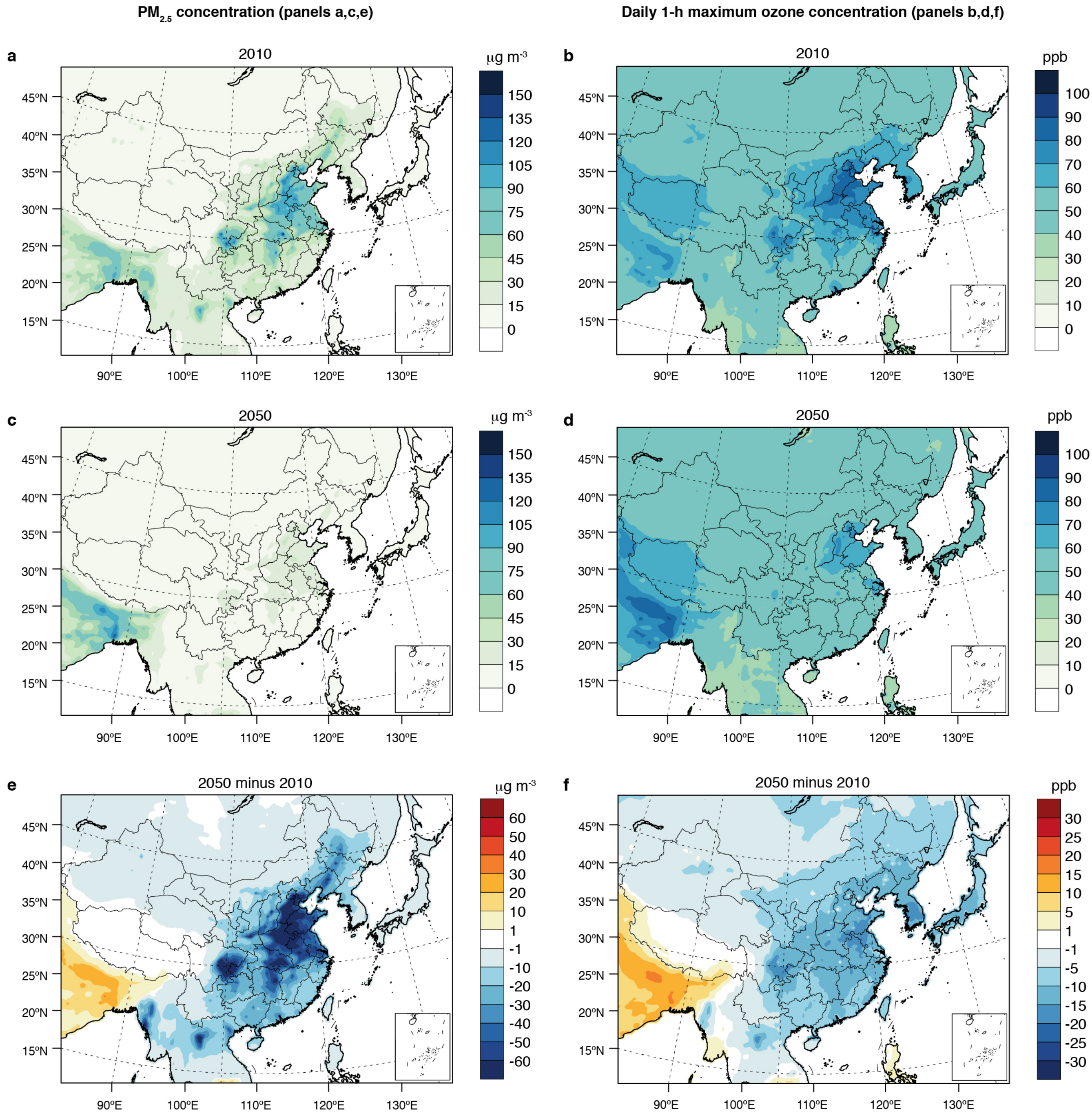
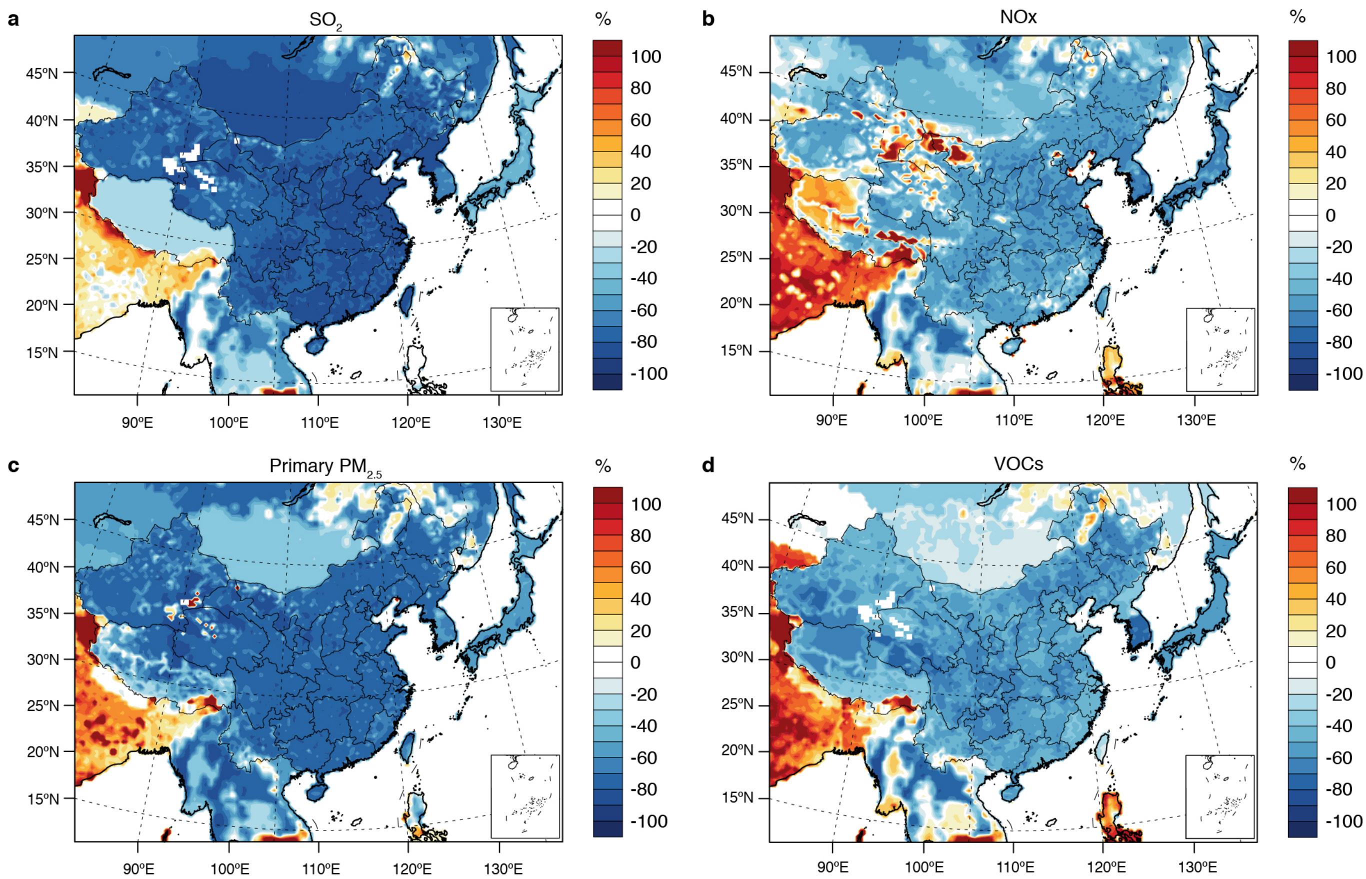
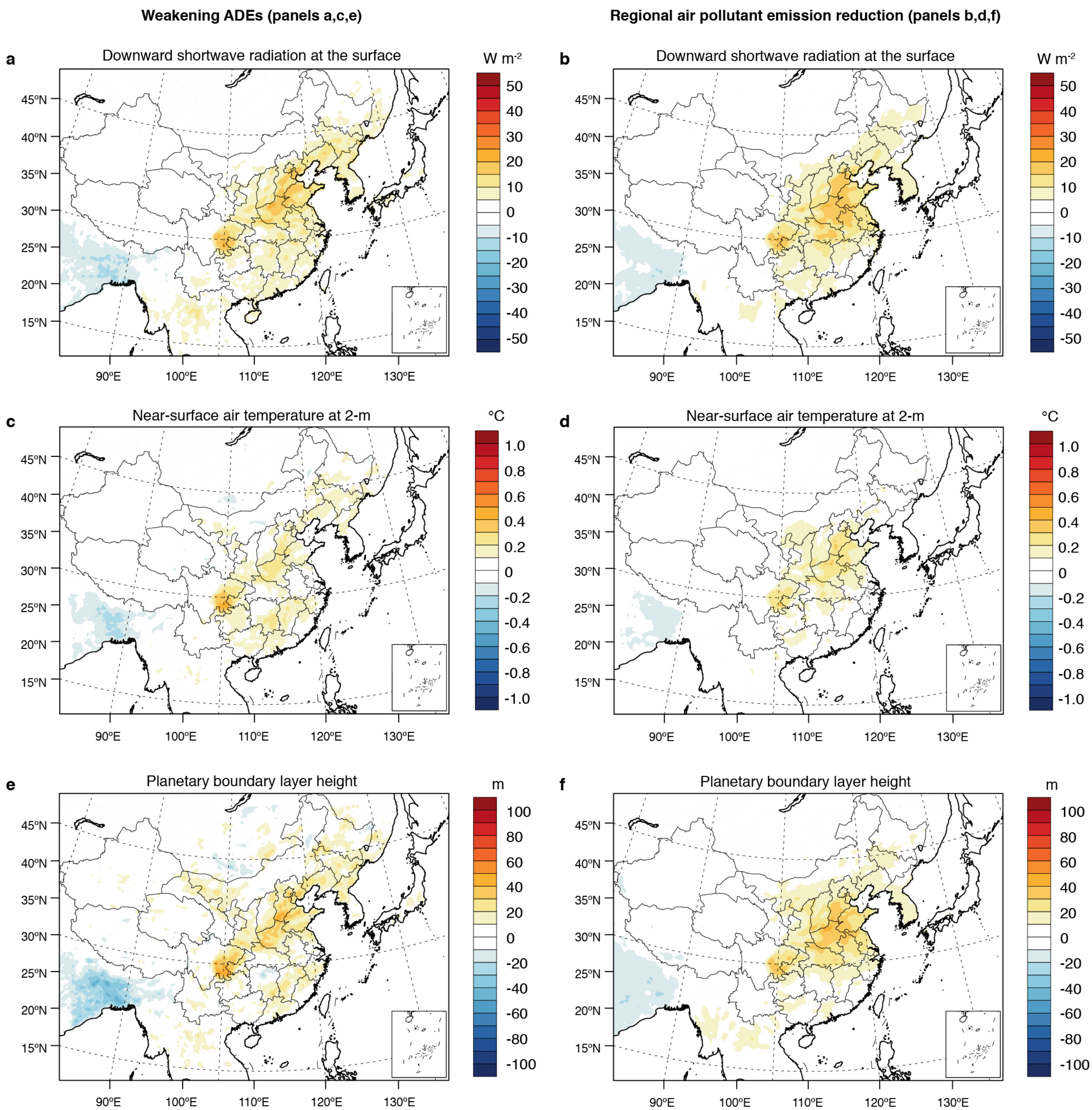


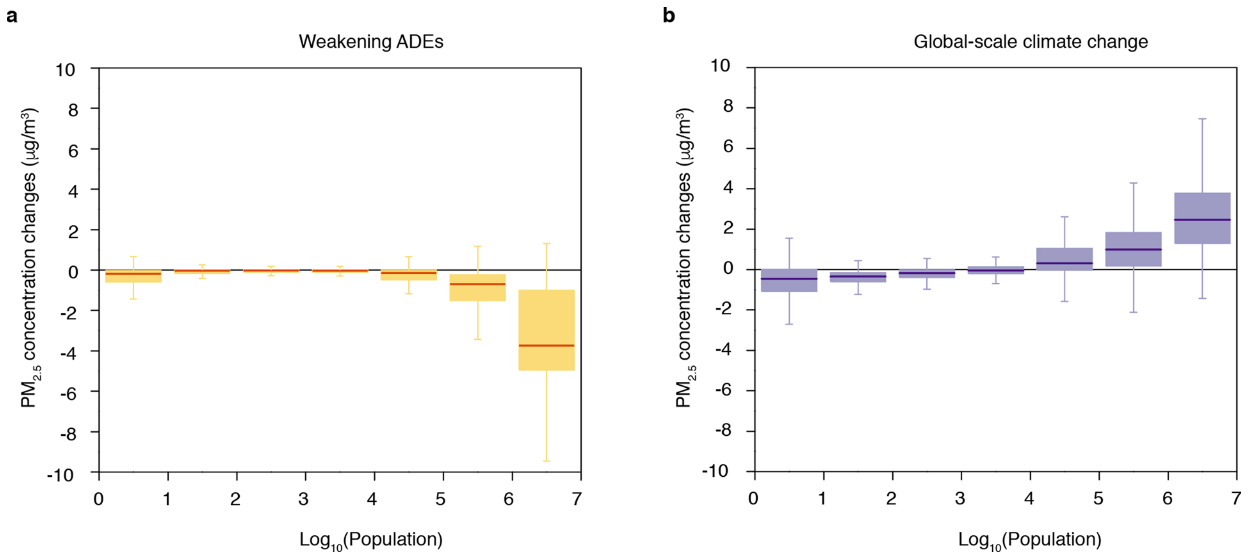
Extended Data Fig. 1 | Projected changes in regional air quality under RCP4.5. Projected changes in annual mean $PM_{2.5}$ concentrations **a**,**c**,**e**, and ozone season (April to September) average of daily 1-hour maximum ozone **b**,**d**,**f**, over East Asia from 2010 to 2050 under RCP4.5.



Extended Data Fig. 2 | Changes in anthropogenic air pollutant emissions under RCP4.5. Changes in anthropogenic emissions of SO_2 **a**, NOx **b**, primary $PM_{2.5}$ **c**, and VOCs **d**, over East Asia from 2010 to 2050 under RCP4.5.



Extended Data Fig. 3 | Comparison of regional climate change caused by weakening ADEs and air pollutant emission reduction. Projected annual mean changes in downward shortwave radiation at the surface **a**,**b**, near-surface air temperature at 2-m **c**,**d**, and planetary boundary layer height **e**,**f**, over East Asia, caused by changing/weakening ADEs (a,c,e, ΔWeakeningADE, from the feedback and no-feedback simulations) and regional air pollutant emission reduction (b,d,f, ΔRegEmisChg) from 2010 to 2050 under RCP4.5.



Extended Data Fig. 4 | Distribution of surface $PM_{2.5}$ concentration changes across grid cells grouped by populations. Projected changes in annual mean $PM_{2.5}$ concentrations over China due to weakening ADEs (a, ΔWeakeningADE) and global-scale climate change (b, ΔGlobalClimChg) from 2010 to 2050 under RCP4.5. Box plot elements: center line, median; box limits, upper (75th) and lower (25th) percentiles; whiskers, 1.5 times the interquartile range.