Health and economic benefit of China’s greenhouse gas mitigation by 2050

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Abstract
As the biggest greenhouse gases (GHGs) emitter, China’s climate mitigation has tremendous contributions to the global carbon and air pollutants reductions. This study is trying to extract the co-benefit on air quality, public health and economic costs in China and worldwide from China’s GHGs mitigation policy. We construct two scenarios, with moderate climate mitigation action worldwide, versus more stringent climate mitigation action in China. We use the GAINS model to predict the GHGs and air pollutants emissions in the two scenarios, and a state-of-the-art global chemical transport model to simulate the annual PM₂.⁵ concentrations. We then use IMED|HEL, which is a health assessment model, to estimate the health impacts and economic cost of PM₂.⁵ pollution in each country. Results show China’s mitigation has significant impact on both air quality and health improvement in eastern China and eastern Asia, a little bit impact in the rest of Asia. The improved air quality could avoid 0.37 million premature deaths due to ambient PM₂.⁵ exposure by 2050s globally, with the majority happening in China. We use the willingness to pay method to estimate the economic benefits from the improved air quality, and find that the reduced ambient PM₂.⁵ concentration could avoid $406 billion and $1206 billion economic costs by 2030s and 2050s globally, with China the largest fraction of 98.5% ($400 billion) and 99.5% ($1200 billion), respectively. The reduced ambient PM₂.⁵ exposure can also avoid 11.3 million cases morbidity globally by 2050s, due to asthma attacks and hospital admissions. Our study shows most of the economic benefits from air quality improvement due to China’s mitigation happens in China, followed by the eastern Asia (such as South Korea and Japan) and the rest of Asia. Health improvement is the main fraction of the potential benefits, such as saving health expenditure, increasing the work time.

1. Introduction
Because of the fast socio-economic development in the past three decades, China is consuming a large amount of fossil fuel. At the same time, China is facing huge pressure in terms of climate change mitigation and air pollution (Dong et al 2015, Peng et al 2018). To address such challenges, China submitted Nationally Determined Contributions (NDCs) to the Paris Agreement to reduce carbon emissions (He 2015). Many studies have suggested that climate mitigations bring significant co-benefits on health and the economy (Zhang Y et al , Xie et al 2018, Vandyck et al 2018, Li et al 2019). At the global level, West et al (2013) estimated the representative concentration pathway 4.5 (RCP 4.5)-equivalent greenhouse
gases (GHGs) mitigation would result in $2.2 \pm 0.8$ million fewer air pollution-related premature deaths globally in 2100, compared with its reference scenario without climate policy. The economic co-benefits are more significant in East Asia than in other regions, about 10–70 times the marginal cost in 2030 (West et al. 2013). McCollum et al. (2013) found that carbon reduction efforts could reduce energy-related health outcomes by about 2–32 million reduction of disability-adjusted life years in the world in 2030. One study from OECD shows the economic costs of outdoor air pollution by 2060 will increase to 1% of global GDP, with highest GDP losses in China (Dellink et al. 2019). Our previous study estimated the co-benefits of climate change mitigation in Asian countries and found that climate change mitigation under the 2 °C goal could reduce 0.79 million premature deaths in 2050 in Asia. The economic benefit is equivalent to 2.8 trillion USD in 2050, about three times of the climate mitigation cost in Asia (Xie et al. 2018).

At the national level, Balbus et al. (2014) estimated that the health outcomes reductions due to the fine particulate matter (PM$_{2.5}$) exposure decline would save the United States $6–30 billion (in 2008 $) by 2020. Another study in the United States found that climate change mitigation would avoid more than 10,000 premature deaths in 2050 and 5,000 premature deaths in 2100 because of air quality improvement, equivalent to a value of statistical life (VSL) of approximately $150 billion (in 2005 $) by 2050 and $1.3 trillion by 2100 (Garcia-Menendez et al. 2015). One study in EU showed the positive health effect could offset the resource costs associated with the clean air policy, which resulted in a net benefits on the economy (Vrontisi et al. 2016). In China, Yang and Teng (2017) showed that compared to 2010 levels, if China reduces its 2030 carbon emissions intensity by 60–65%, it would reduce 78.85% of sulfur dioxide, 77.56% of nitrogen oxide, and 83.32% PM$_{2.5}$ emissions by 2030. Health improvement constitutes a substantial fraction of the potential benefits, along with averted adaptation costs and residual damage. Li et al. (2019) recently estimated the co-benefits on air quality and human health in 2030 from China’s targeting CO$_2$ intensity reductions, and found that 149,400 (95% confidence interval (CI): 125,400–173,300) deaths would be avoided in 2030 in China, including both PM$_{2.5}$ and ozone. For other regions, total avoided premature deaths are 1,200 (900–1,600) in South Korea, 3,500 (2,800–4,300) in Japan, and 1,900 (1,400–2,500) in the US, respectively (Li et al. 2019).

Previous studies have focused on the health benefits of climate mitigation at the aggregate global level or short term until 2030, and they typically used a one-way assessment: from air pollutant emissions to the adverse health outcomes. Few studies attempted to estimate both the health and economic co-benefits (such as health expenditure saving and work supply change), from China’s climate mitigation policy to China and transboundary regions in the long term. In this study, we aim to distinguish benefits of China’s climate mitigation to China and other countries towards 2050. Moreover, we adopted an integrated methodology that includes the environment-health-economy by combining an economic model, a global chemistry transport model, and a health assessment model to evaluate the interactions among the economic systems, environment and human health in China. This study differs from our previous one (Xie et al. 2018) which estimated the co-benefit on air quality and health in Asia from global climate policy, as for this study we quantify the co-benefits on air quality and health in China and downwind regions from different climate policies in China only.

2. Methodology

2.1. Integrated assessment methods

This study combines GAINS (Global Air Pollution Information and Simulation model) from International Institute for Applied Systems Analysis (IIASA), CAM-Chem (a global chemistry-climate model), and IMED/HEL (Integrated Model of Economy, Energy and Environment for Sustainable Development/Health impact assessment) from Peking University to estimate the co-benefits on global health and economic from air quality improvement due to different climate policies in China (see figure S1 (available online at https://stacks.iop.org/ERL/15/104042/mmedia) in the supporting material). This approach has been used in our previous studies (Xie et al. 2016, 2018, 2019, Wu et al. 2017, Tian et al. 2018). We use GAINS model to predict air pollutants emissions in the future under different climate policies, and the CAM-Chem model to simulate the future air quality from the air pollutant emission changes, and the IMED/HEL model to quantify the health impact of air pollution, including mortality, morbidity, work time loss, expenditure and VSL. The specific models are introduced below.

2.1.1. GAINS model

GAINS model was developed by IIASA in Austria, to estimate air pollutant emissions and design abatement strategies. It provides a consistent framework for estimating emissions, mitigation potentials, and costs for air pollutants (SO$_2$, NO$_x$, PM, NH$_3$, NMVOC) and GHGs included in the Kyoto protocol. Documentation of the model introduction and the principal data, assumptions, and results are freely available online (IIASA website: https://gains.iiasa.ac.at/gains/, accessed Feb 25, 2020). Various air-pollutant-mitigation technologies were considered in GAINS model to estimate the air pollution control policy. In this study, GAINS-China model was used to estimate the air
pollutant emissions and pollution control costs data for China. Large amount of institutions employs the GAINS to explore mitigation potentials of air pollutants and GHG on cost-effective manner, under multiple objectives (e.g. environmental impacts and climate target) (such as Amann et al 2008, Zhang X et al 2017).

2.1.2. CAM-chem global air quality model

The state-of-the-art global air quality model CAM-chem is used in this study, which is based on the global Community Atmosphere Model (CAM) version 4, the atmospheric component of the Community Earth System Model (CESM, v1.2.2) (Lamarque et al 2012, Tilmes et al 2015, 2016). The model uses a horizontal grid with a resolution of 2.5° × 1.9° (longitude × latitude), and 56 vertical levels between the surface and 4 hPa (=40 km) with a time step of 1800 s. The NASA Global Modeling and Assimilation Office GEOS-5 meteorology is used to drive the model. For all the simulations, we run CAM-chem for six consecutive years from 2012–2017 driven by the same GEOS-5 meteorology, with the first year as spin-up and the rest five-year average for data analysis. We apply the same meteorology for all the runs, to eliminate the influences from future climate changes on air quality. Chemically active stratospheric species (such as O3, NO, NO2 and N2O5) are prescribed as monthly mean distribution using the climatology from the Whole Atmospheric Community Climate Model simulations (Lamarque et al 2012, Zhang Y et al 2016a).

Monthly temporal variations for the anthropogenic air pollutants are added by using the monthly emission factors from REnalysis of the TROPospheric chemical composition (RETRO) and the NMVOCs are re-specified into CAM-chem chemical speciations (West et al 2013, Fry et al 2014, Silva et al 2016, Zhang et al 2016a, 2016b, 2017), following the discussion by the CAM-chem model (Lamarque et al 2013). The Model of Emissions of Gases and Aerosols from Nature (MEGAN-v2.1, Guenther et al 2012) simulates biogenic emissions for 150 compounds online within CAM-chem. Lightning NOx emissions are calculated online with 3.21 TgN yr−1 (five-year average), which is lower than the average of ACCMIP models for 2000, but within the range (Young et al 2013). Other natural emissions (soil, ocean, and volcano) are from the standard CAM-chem emission files (Lamarque et al 2012), and remain the same for all of the simulations (Emmons et al 2010).

2.1.3. IMED|HEL model

The IMED|HEL model evaluates the health impacts of PM2.5 exposure, including six kinds of morbidity endpoints, mortality, work-loss days (WLDs), health expenditure and VSL. The mortality is calculated by using the nonlinear integrated exposure-response functions (IER, Burnett et al 2014) and latest Global Exposure Mortality Model (GEMM, Burnett et al 2018). The relative risks (RRs) for the IER function are from the lookup table compiled by Apte et al (2015), to be consistent with the analysis in Burnett et al (2018). The Ts present the uncertainties of parameters in the exposure-response functions derived from the epidemiologic literature, and neglect those from the emissions and simulated PM2.5 concentration caused by the coarse resolution in the CAM-Chem model. The medical expenditure and the VSL loss are quantified by assuming linear relationship with the PM2.5-related premature deaths by using health service price in China (Xie et al 2016), and we estimated health service price for other countries based on the data in China and per capita GDP in other countries (Xie et al 2018). For the VSL-related economic loss, we used the VSL from the latest China’s study, 2.3 million Chinese yuan (CNV) (2017 value) for middle and low-income countries with the elasticity 1.2 according to the World Bank classification (https://datahelpdesk.worldbank.org/knowledgebase/articles/378344-how-does-the-world-bank-classify-countries) (Jin et al 2020, Robinson et al 2019). For the high-income countries, we used VSL from OECD study with elasticity 0.8 (OECD 2016). The annual total WLDs is the sum of the WLD because of the morbidity and the cumulative WLD from the mortality of the working population. The annual average per capita work loss rate was calculated by dividing the WLD by all the working population and annual working days. In this study, the settings of IMED|HEL model is referring to our previous studies (Xie et al 2016, Wu et al 2017, Tian et al 2018).

2.2. Scenarios setting

The International Energy Agency (IEA) publishes world energy outlook (World Energy Outlook, WEO) every year. This outlook includes a comprehensive review of global energy markets, covering key energy policy, technology and financial trends across oil, gas, coal, nuclear, renewable energy, energy efficiency and electricity markets for each region (IEA 2016). IEA releases three climate scenarios, including the Current Policy Scenario (CPS), New Policy Scenario (NPS), and 450 scenario. The CPS is baseline scenario which assumes no intensive climate policy developments. The NPS includes all key proposed policy developments, such as all the commitments of NDCs. The 450 scenario represents a scenario to meet the requirement of limiting global warming under 2 °C. In this study, we choose the WEO2016_NPS scenario as the reference scenario (C0), and WEO2016_450 for China and WEO2016_NPS for other countries (C1) as the mitigation scenario. The global anthropogenic emissions from these two scenarios for present (2015 s), near-term (2030 s) and mid-term (2050 s), are fed into the CAM-Chem model to simulate the future air quality changes (table S1 in the supporting).
C0: WEO2016_NPS is the NPS, which includes all key proposed policy developments, such as all the commitments of NDCs. The NPS shows the way that governments plan on their energy sectors development over the coming years. It includes the policies that are already in place in the NDCs, but it also takes into account the aims, targets and intentions.

C1: Stringent climate mitigation scenario in China only, and NPS scenario outside China, under which China has more intensive carbon reduction target while other countries have the same climate policies as in C0 scenario. In this scenario, the Chinese government controls fossil fuel consumption, develops clean energy, improves energy efficiency and reduces energy intensity. It aims to limit the average global temperature increase in 2100 to 2°C above pre-industrial levels. In the WEO2016_450 scenario, fossil fuel consumption is much lower than WEO2016_NPS in China, and air pollutants emissions are also reduced (IEA 2016). It has also been used as a yardstick in reports from the Intergovernmental Panel on Climate Change. The WEO2016_450 scenario is a widely recognized benchmark for government policies and company strategies on climate change.

3. Results

3.1. Co-benefit of air quality improvement

Figure 1 shows the air pollutants emission change from C0 scenario to C1 scenario in 2050 s in China. The emission changes in 2030 s are shown in figure S2. Climate policy reduces the fossil fuel consumption, therefore, the emissions of the air pollutants precursor such as NOx and SO2 will decline in C1 scenario. From figure 1 we see that NOx and SO2 will decline by 20% to 30% in 2050 s compared with 2015, while for OC, BC and NH3, the reductions are around 6–8%. On average, CO reduces 17.1 Tg yr\(^{-1}\) at 2050 s, which is 10.6 Tg yr\(^{-1}\) higher than the year 2030 s (figure S2). At the same time, NOx decreases 2.9 Tg yr\(^{-1}\), and SO2 decreases 3.3 Tg yr\(^{-1}\) by 2050, almost double the changes in 2030 s (figure S2). BC and NH3 also see larger decreases in 2050 s compared with 2030. At the regional level, most of the air pollutants emissions are reduced in the North and East of China, such as Shandong, Henan, Hebei, Anhui and Jiangsu. In the provinces in the West of China, such as Xinjiang, Qinghai, Inner Mongolia, Yunnan and Guizhou, the air pollutants emissions are very low and the emissions reductions are also limited.

We simulated the annual average PM\(_{2.5}\) concentration in 2015, and concentration changes in C0 and C1 in 2030 s and 2050 s using CAM-chem model (figure 2). In 2015, PM\(_{2.5}\) concentration is the same for both C0 and C1, since the climate mitigation policy is the same in our assumption in the base year. From figure 2 we see that, the PM\(_{2.5}\) concentration will decrease around 20 μg m\(^{-3}\) in north China in 2030 s and more provinces will experience significant reduction (more than 20 μg m\(^{-3}\)) by 2050 s even in C0 scenario, and the provinces near the over-polluted regions also have around 10 μg m\(^{-3}\) decrease. Comparing with...
C0 scenario, more provinces in China experience remarkable PM$_{2.5}$ concentration reduction, larger than 10 $\mu g\, m^{-3}$ in 2050 s. Meanwhile, the provinces with more than 20 $\mu g\, m^{-3}$ PM$_{2.5}$ concentration in C1 scenario will extend to Northeast and Southwest of China. The provinces with slight PM$_{2.5}$ concentration reduction will extend to Northwest of China. Table S2 in the appendix shows the PM$_{2.5}$ concentration in North China in 2050, which is from 26.1 $\mu g\, m^{-3}$ to 96.5 $\mu g\, m^{-3}$ in the C0 scenario and from 23.3 $\mu g\, m^{-3}$ to 75.5 $\mu g\, m^{-3}$ in the C1 scenario.

Under the C1 scenario, PM$_{2.5}$ concentration decreases more significantly in China compared with C0 scenario. The co-benefits (C1-C0) for annual PM$_{2.5}$ concentration in China are usually larger than 2.0 $\mu g\, m^{-3}$ in the north and east of China in 2030 s (figure 3(a)). However, more significant reduction are seen in the 2050 s. Besides China, other East Asian countries also has co-benefit on PM$_{2.5}$ concentration reduction from China’s climate mitigation. Figure 3 shows the PM$_{2.5}$ concentration reduction around 2 to 4 $\mu g\, m^{-3}$ in 2030 s and 4 to 6 $\mu g\, m^{-3}$ in 2050 s in the East Asia, especially in the Korea and west of Japan. The South Asia experiences tiny PM$_{2.5}$ concentration reduction, but reduction is smaller compared with East Asia. For other regions, the PM$_{2.5}$ concentration change is not significant.

### 3.2. Health impact and economic co-benefits

Climate mitigation can improve the air quality and then reduce air pollution attributable premature deaths. In C0 scenario, the PM$_{2.5}$-related premature deaths are around 6.33 million globally in 2030 s and it will decrease to 6.40 million in 2050 s by using non-linear IER function. While, under the stringent climate mitigation policy the premature deaths will be reduced to 6.36 million in 2030 s, and 6.03 million in 2050 s in the C1 scenario. The avoided premature deaths from China’s mitigation policy are 0.17 and 0.37 millions in 2030 s and 2050 s globally. Using non-linear GEMM function, C0 scenario, the PM$_{2.5}$-related premature deaths are around 9.69 million globally in 2030 s and it will increase to 10.69 million in 2050 s. While, under the stringent climate mitigation policy the premature deaths will be reduced to 9.61 million in 2030 s, and 10.45 million in 2050 s in the C1 scenario. The avoided premature deaths from China’s mitigation policy are 0.09 and 0.24 millions in 2030 s and 2050 s globally. Asian countries share the most of the avoided premature deaths, especially China, India, South East Asia and East Asia (figure S3, table S3). In China, the air quality improvement could reduce the premature deaths due to air pollution by 0.17 and 0.36 million in 2030 s and 2050 s separately, around 97% of globally total avoided deaths. Southeast Asia has the second largest co-benefits, about 2900 avoided premature deaths in 2030 and 7,600 in 2050. For India, the avoided premature deaths from China’s climate mitigation are 280 in 2030 s and 740 in 2050 s. For other regions, the health co-benefit is not significant.

Previous studies have shown that different exposure response functions (ERFs) could have large uncertainties on the air pollution mortality analysis (Burnett et al. 2018, Ostro et al. 2018), and usually much larger than the uncertainty from concentration changes (Crippa et al. 2019, Jin et al. 2019). Here we estimate the avoided PM$_{2.5}$-related mortality in nine Asian countries by adopting three different ERFs: linear (Krewski et al. 2009), non-linear GEMM (Burnett et al. 2018), and non-linear IER (Apte et al. 2015) (figure 4). The co-benefits for the avoided premature mortality due to ambient PM$_{2.5}$ exposure typically range in 2%–8% in most countries except India. When using the two non-linear functions (GEMM and IER), we get the similar co-benefits for the avoided premature mortality, though the air pollution related mortality burdens are significantly different by using different ERFs (figure S4). The mortality burden estimated using the non-linear IER function are smaller than those using the linear or the non-linear GEMM functions (figure S4). For countries with higher PM$_{2.5}$ exposure levels, the linear IER yields the highest estimated mortality values, and the IER yields the lowest. In 2015, the estimated mortality under the C0 scenario in China and India based on the IER function was 1.68 (95% CI: 0.85–2.24) and 0.97 (95% CI: 0.54–1.37) million, respectively, consistent with previous studies (Lelieveld et al. 2015). By 2050 s, the estimated mortality burden under the C0 scenario would be 3.60 (95% CI: 2.65–4.41) and 2.48 (95% CI: 1.76–3.13) million for China and India, respectively, using the IER function. By applying the GEMM function, we estimated the PM$_{2.5}$-related premature mortality is 2.87 million in China and 1.86 million in India in 2015 (table S4), and by 2050 they decrease to 2.05 (95% CI: 1.44–2.51) and 2.48 (95% CI: 1.44–1.73) million, respectively.

We then use the willingness to pay method (WTP) to estimate the economic benefits of China’s climate mitigation policy for China and other regions. Our results show air pollution leads to a heavy burden on the economy in the world. Economic cost due to PM$_{2.5}$ exposure are over $9000 billion globally in 2030 s, and it will increase to $13 trillion in 2050 s under the C0 scenario. Stringent Climate policy in China (WEO2016_450) will save $406 billion in 2030 s and $1206 billion in 2050 s globally. At the regional level, China has the most of the co-benefits from China’s climate mitigation. In 2030 s, the avoided economic cost due to PM$_{2.5}$ reduction is around $400 billion, and it will increase to $1200 billion in 2050 in China. Some part of the avoided economic cost increase is due to the economic development in China. Most of the avoided economic cost is because of the avoided premature deaths due to air pollution related mortality.
quality improvement. Following China, the Southeast Asia has $2.6 billion economic benefit from China’s climate mitigation in 2030 s, and $10.3 billion in 2050 s.

Climate change mitigation also has co-benefits on reducing the PM$_{2.5}$-related morbidity, including the asthma attack, chronic bronchitis, respiratory hospital admission including respiratory, cardiovascular and cerebrovascular disease (the RRs for all the PM$_{2.5}$-attributed morbidity are seen in table S5). Figure S5 shows the total morbidity due to PM$_{2.5}$ exposure and the morbidity reduction due to China’s climate mitigation policy. Air quality improvement can reduce the hospital admissions significantly both in 2030 s and 2050 s. The stringent climate policy in China can avoid 5.6 million cases morbidity globally in 2030 s, and 11.3 million in 2050 s. China has the largest fraction, about 5.1 million and 10.8 million in 2030 s and 2050 s. Southeast Asia shares significant co-benefits from China’s climate mitigation, about 9,500 reduction of morbidity in 2030 s and 0.2 million in 2050 s. Besides, India and Japan also have co-benefit of avoided morbidity, about 1,000–1,500 in 2030 s and 2,000–4,000 in 2050 s, respectively.

Climate mitigation also brings co-benefits on health expenditure saving due to air pollution-related morbidity decrease. We use the Cost of Illness (COI) method to estimate the total health expenditure saving from China’s climate mitigation, based on the number of each morbidity. The PM$_{2.5}$-related health
Figure 3. Co-benefits for annual PM$_{2.5}$ concentration changes in 2030 (a) and 2050 (b) in Asian countries between C0 and C1 scenario. The unit is µg m$^{-3}$.

expenditure was $8.9 billion in 2015 in China in the C0 scenario. While in the C1 scenario, China gets the most expenditure saving from the mitigation policy. In 2030 s, PM$_{2.5}$-related health expenditure is about $18.4 billion in China, and climate policy can reduce $1.2 billion expenditure in 2030 s. In 2050 s, the health expenditure saving will be much higher than 2030 s, around $4.1 billion. The Southeast Asia also has economic benefit from China’s mitigation, about $7.7 million in 2030 s and $34.6 million in 2050 s. India has lower economic benefits compared with China and Southeast Asia, about $1.4 million in 2030 s and $7.6 million in 2050 s.

3.3. Worktime loss changes

Health impacts on labor force can reduce work time, which has negative impacts on the labor supply and the economy (Wu et al 2017, Xie et al 2018, 2019). Figure 5 shows the worktime loss and changes due to China’s climate mitigation policy in 2030 and 2050. Asian countries have most of the co-benefit on avoided worktime loss. In the C0 scenario, China, India and Rest of Asia have the higher per capita worktime loss from PM$_{2.5}$ exposure, about 16.5 h, 15.9 h and 17.1 h in 2030 s. In 2050 s, the worktime loss will increase to 40.0 h in China, 44.3 h in India and 39.0 h in rest of Asia under C0 scenario, respectively. Under China’s climate mitigation, worktime change is small in 2030 s even in China. However, it will become more significant in 2050 s due to larger air quality improvement. For example, China’s climate mitigation can reduce the per capita work time loss about 5.6 h in China and 0.21 h in Japan in 2050 s. In Southeast Asia and Rest of Asia, per capita work time loss reduction is about 0.2 h in 2050 s.

4. Discussions

In this study, we combined GAINS-China, CAM-Chem and IMED|HEL models to quantify the benefit of climate mitigation policy in China and the impacts to the transboundary regions. Our result shows climate mitigation can bring significant benefit on air quality and health in the long term in China, especially in north and east of China. At the provincial level, cost-benefit is quite different among 30 provinces (tables S6–S8). For these provinces with higher population density and more heavy industry, such as Shandong, Henan, Hubei, Anhui and Hebei, mitigation policy could bring more benefit on the health and economy (table S8). While for the provinces with relatively good air quality, less populous and industrial regions, co-benefit is not significant, such as Yunnan, Guizhou, Xinjiang and Gansu in the west of China. It also has positive impact on the air quality improvement and health for East Asia and southeast Asia, such as South Korea and Japan. Both for the air pollution control and climate mitigation, cooperation is essential for neighboring regions.

We evaluated the model’s performance in simulating the annual PM$_{2.5}$ concentration by comparing the model simulation in 2015 with three years surface observation data in China from 2014 to 2016 (table S9 in the appendix). For all the years, we have a pretty good correlation coefficient for the model performance (with R larger than 0.68) which are comparable with previous studies (Li et al 2018, Shindell et al 2018), though our model tends to overestimate PM$_{2.5}$ concentration. The difficulties for atmospheric chemistry models, especially for global models with coarse resolution, in capturing high concentrations of PM$_{2.5}$ especially in urban areas have been discussed extensively in the literature (Sun et al 2014), which could be caused by missing emissions, formation pathways such as in the case of secondary organic aerosols (Fu et al 2012) or spatial heterogeneity in emissions, meteorology and chemistry. A previous study which estimated the uncertainty for the health impact by applying seven PM$_{2.5}$ products,
Figure 4. The co-benefits on avoided premature deaths in nine Asia countries under stringent climate policy in China between C0 and C1 scenario in 2050s, under three different ERFs: linear (Krewski et al. 2009), non-linear GEMM (Burnett et al. 2018), and non-linear IER (Apte et al. 2015). The fractions are calculated as (C1-C0)/C0 × 100% in 2050s.
the air pollution control and climate mitigation via series of policy plan, including the development of renewable energy, end-of-pipe technology and regular environment protection actions. The fossil fuel consumption and air pollutants emissions decrease more than the model projections. For the regions under the intensive control plan, the air quality improvement may exceed the simulation from our model.

Climate mitigation absolutely has benefits on the air quality and human health (Xie et al 2019). Many studies have documented climate mitigation has net benefit to humanity. If we consider the co-benefit both on human and other systems on the earth (such as ecosystems, ocean), the total benefit will be much higher than our estimation. On the other hand, climate mitigation also costs a lot, especially for developing countries. Disadvantaged countries aim for economic growth and industrialization, which need more energy. At the same time, the technology is usually not so advanced in these countries. High-efficiency technology is expensive for them. The air pollution reduction is a heavy burden and may have negative impact on their economy. For example, China is under fast development and the imposing restrictions on the fossil fuel will have negative impacts on the energy-intensive sectors in the short-term, which will be sure to have unacceptable impacts. In the long-term, restriction on the traditional energy-intensive sectors will stimulate the low-carbon and high energy efficiency technology, which will actuate the development of the relative sectors.

There are some limitations in the setting of our study. This study only estimates the co-benefit of China’s climate mitigation policy to China and transboundary regions, and ignores the climate mitigation in other countries. The estimated emissions and concentration will be much higher than considering global climate mitigation (West et al 2013, Zhang et al, 2017). In performing future air quality simulations, we also neglect the possible climate changes from the global and China climate policies on the influence of air quality. Study has shown that the climate change could have significant effect for ambient ozone but not for PM$_{2.5}$ (Jacob and Winner 2009, Fiore et al 2012, Zhang et al 2017b). This study used air pollution control strategy in the GAINS model, which only reflected the policy implications around 2015. Our estimations for the co-benefits for air quality and
health will be higher since GAINS model is not able to capture the latest stringent air pollution policies in China after 2015. In the uncertainty analysis, we do not consider uncertainties from emissions and simulated air pollutant concentration, which could be quite large given our transport models large biases in predicting current PM$_{2.5}$ levels in China.

5. Conclusions

This study uses the integrated assessment methods to distinguish the air quality, human health and economy co-benefits from China’s climate mitigation policies in China and other transboundary regions. We find that China’s stringent mitigation policy, which aims to limit the average global temperature increase to 2 $^\circ$C s above pre-industrial levels by 2100, will have significant co-benefits for China’s PM$_{2.5}$ reduction and other regions, especially in the downwind countries, such as Korea and Japan, compared with its less stringent policy (the commitment of UN NDCs target). The stringent policy will contribute 2.0 to 4.0 $\mu$g m$^{-3}$ PM$_{2.5}$ reduction in the north and east of China in the 2030 s, and the benefit will be higher by 2050 s. The policy can avoid 0.37 million premature deaths attributable to ambient PM$_{2.5}$ exposure by 2050 s globally. More than 95% of avoided premature deaths will happen in China, following by Korea which are 3800 avoided deaths, and Japan which are 2000 avoided deaths by 2050 s. Due to the large population size, India also has 1400 avoided premature deaths by 2050 s.

We then use the WTP method to estimate the economic benefits from the improved air quality, and find that the reduced ambient PM$_{2.5}$ concentration could avoid $\$406$ billion and $\$1206$ billion economic costs in 2030 s and 2050 s globally, with China the largest fraction of 98.5% ($400 billion) and 99.5% ($1200 billion), respectively. Beside the avoided mortality, we also estimate other health endpoints, such as morbidity due to asthma attack and hospital admissions, as well as the work time loss. PM$_{2.5}$ reduction due to China’s stringent climate mitigation can avoid 5.6 million cases morbidity globally in 2030 s, and almost double that by 2050 s. We then use the COI method to estimate the total health expenditure saving, from the avoided morbidity due to stringent climate policy in China. Globally, the health expenditure saving is about $1.2$ billion by 2030 s and $4.1$ billion by 2050 s. Besides, PM$_{2.5}$ reduction also lowers per capita work time loss due to the morbidity and mortality. Worktime loss reduction will have positive on the economy and public welfare. Considering increasing of work time, total benefit of China’s climate mitigation will much higher than current estimation both for China and other transboundary regions.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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