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Changes of air quality and its associated health and economic burden in 31 provincial capital cities in China during COVID-19 pandemic

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ABSTRACT

With outbreak of the novel coronavirus disease (COVID-19), immediate prevention and control actions were imposed in China. Here, we conducted a timely investigation on the changes of air quality, associated health burden and economic loss during the COVID-19 pandemic (January 1 to May 2, 2020). We found an overall improvement of air quality by analyzing data from 31 provincial cities, due to varying degrees of NO_2, $PM_{2.5}$, PM_{10} and CO reductions outweighing the significant O_3 increase. Such improvement corresponds to a total avoided premature mortality of 9410 (7273–11,144) in the 31 cities by comparing the health burdens between 2019 and 2020. NO_2 reduction was the largest contributor (55%) to this health benefit, far exceeding $PM_{2.5}$ (10.9%) and PM_{10} (23.9%). O_3 instead was the only negative factor among six pollutants. The period with the largest daily avoided deaths was rather not the period with strict lockdown but that during February 25 to March 31, due to largest reduction of NO_2 and smallest increase of O_3. Southwest, Central and East China were regions with relatively high daily avoided deaths, while for some cities in Northeast China, the air pollution was even worse, therefore could cause more deaths than 2019. Correspondingly, the avoided health economic loss attributable to air quality improvement was 19.4 (15.0–23.0) billion. Its distribution was generally similar to results of health burden, except that due to regional differences in willingness to pay to reduce risks of premature deaths, East China became the region with largest daily avoided economic loss. Our results here quantitatively assess the effects of short-term control measures on changes of air quality as well as its associated health and economic burden, and such information is beneficial to future air pollution control.

1. Introduction

A novel coronavirus (later named as SARS-CoV-2) was first discovered at the end of 2019, and it outbroke in China then quickly spread over the globe (Zhu et al. 2020). As of 13 September 2020, the number of confirmed cases of the disease caused by SARS-CoV-2 (COVID-19) was 28,940,233 with a death toll of 924,569 worldwide (https://www.worldometers.info/coronavirus/). To contain the COVID-19 epidemic, the central government of China imposed a lockdown in Wuhan (virus epicenter of China) on January 23, 2020, and then almost all provinces launched the Level-1 public health emergency response (Li et al. 2020; Wang et al. 2020a; Wang et al. 2020b). The outdoor activities of people (traffic, industry, recreation etc.) were largely prohibited. The whole country was in an unprecedentedly state of shutdown for more than one month. These control measures could greatly affect emissions of air pollutants and the air quality (Wang and Su 2020; Xu et al. 2020a; Xu et al. 2020c). It is known that a wide range of adverse health outcomes including asthma, respiratory disease, cardiovascular disease, lung cancer (Cascio and Long 2018; Fuertes et al. 2020; Guo et al. 2019; Knibbs et al. 2018; Rodriguez-Villamizar et al. 2015; Sun et al. 2019), etc., are associated with air pollution. While great efforts in recent years have been made to reduce air pollution in particularly fine particulate matter ($PM_{2.5}$) concentration, China is still suffering relatively heavy air pollution and potentially high health risks particularly in densely populated regions (Nie et al. 2018; Sahu et al. 2020; Shen et al. 2017; Shen et al. 2020). Haze events still occurred due to that enhanced

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production of secondary aerosol components might compensate the reduced primary emissions (Chang et al. 2020; Huang et al. 2020b; Le et al. 2020; Sun et al. 2020; Wang et al. 2020a), yet an overall improvement of air quality was very probably during COVID-19 period (Bao and Zhang 2020; Huang et al. 2020a; Shi and Brasseur 2020; Xu et al. 2020b). In what extent this improvement influences the health burden, and how large is the economic cost associated with the change of air quality during COVID-19 pandemic? This work aims to investigate and estimate such effects in China.

Previously, a large number of studies have estimated the mortality attributable to air pollution in China. For examples, Lelieveld et al. (2015) estimated that 1.36 million premature deaths in China were attributed to outdoor air pollution ($PM_{2.5}$ and O_3) in 2010; Hu et al. (2017) estimated a total of 1.3 million excess mortality due to $PM_{2.5}$ exposure in 2013; Cohen et al. (2017) presented the 25-year trend of global burden of disease attributable to ambient air pollution, and implied that $PM_{2.5}$ caused 1.1 million premature deaths over China in 2015; Xue et al. (2019) calculated that under the Action Plan of Air Pollution Prevention and Control (2013–2017), there were still 1 million premature deaths attributable to $PM_{2.5}$ exposure in China in 2017. Many of these earlier studies focus on long-term exposure, short-term health effects attributable to air pollutants should not be ignored. For instance, a total of 169,862 additional deaths was estimated from short-term $PM_{2.5}$ exposure throughout China in 2015 (Li et al. 2019b), and the national all-cause premature mortalities attributable to all air pollutants was 1.35 million in 2017 (Yao et al. 2020). Wang et al. (2019) investigated the association of daily mortality with short-term exposure to $PM_{2.5}$ and its constituents in Shanghai.

Furthermore, air pollution is also a detriment to things that individuals fundamentally value, such as leisure, consumption and life itself (Li et al., 2016). The economic loss can be used to evaluate such value, and the value of statistical life (VSL) is an indicator to measure economic loss, which aggregates individuals' willingness to pay (WTP) for marginal reductions in their risks of premature deaths. Zhao et al. (2016) estimated that air pollution in Beijing caused a health economic loss equivalent to 583.02 million RMB in 2012 (0.03% of its GDP). Some other studies estimate much greater losses. For example, Han et al. (2019) estimated 40,555 million USD (2.86% of its GDP) loss in Guangxi province from 2011 to 2016, Yao et al. (2020) reported a loss of 2062.52 billion RMB (2.5% of national GDP) in 2017 in China.

Here we provide a timely investigation on the health burden and economic loss attributable to short-term exposure to air pollutants in China during the COVID-19 pandemic. We aim to reasonably estimate changes of the air quality as well as its associated premature deaths and economic loss in different regions of China during different stages of the pandemic by using data from 31 provincial capital cities. The results provide additional knowledge to help assess the impacts of COVID-19 pandemic.

2. Data and methods

2.1. Data sources

2.1.1. Study period, cities and air pollutants

The COVID-19 pandemic period investigated here was from January 1 to May 2, 2020. It was divided into five stages: Stage 1 (January 1 to 24) was the normal period before quarantine but the virus already transmitted among people, and the deaths during this period were later corrected in the COVID-19 death toll of China; Stage 2 (January 25 to February 9) was the extended Spring Festival holiday with strictest lockdown measures; Stage 3 (February 10 to 24) was the period when most provinces were still with Level-1 public health emergency response, but production activities began to resume; Stage 4 (February 25 to March 31) was the period when most provinces lowered the public health emergency response to Level-2 and production activities gradually recovered; Stage 5 (April 1 to May 2) was the period with Level-3 public health emergency response, and human activities basically resumed to normal in China with necessary prevention measures. Note this four-month period also includes a period before COVID-19 outbreak and periods with mild control measures, we believe such analysis should provide a more comprehensive understanding on influences of the pandemic than those based only on a short lockdown period.

Table 1
The exposure-response coefficients in all-cause mortality of each air pollutant.

Disease category	Air pollutants	Exposure-Response Coefficient (β/%)	Reference
All-cause mortality	$PM_{2.5}$ (10 μg m^{-3})	0.38 (0.31–0.45)	Shang et al. (2013)
	PM_{10} (10 μg m^{-3})	0.31 (0.22–0.41)	Lai et al. (2013)
	SO_2 (10 μg m^{-3})	0.90 (0.60–1.10)	Ma and Cui (2016)
	NO_2 (10 μg m^{-3})	1.40 (1.10–1.60)	Ma and Cui (2016)
	CO (1 mg m^{-3})	3.70 (2.88–4.51)	Shang et al. (2013)
	O_{3_8h} (10 μg m^{-3})	0.40 (0.30–0.50)	Dong et al. (2016)

The study area included 31 provincial capitals excluding Taiwan, Hong Kong and Macao due to lack of data. These cities are grouped into seven regions: North China (Beijing, Tianjin, Shijiazhuang, Taiyuan, Hohhot), Northeast China (Shenyang, Changchun, Harbin), East China (Shanghai, Nanjing, Hangzhou, Hefei, Fuzhou, Nanchang, Jinan), Central China (Zhengzhou, Wuhan, Changsha), South China (Guangzhou, Nanning, Haikou), Southwest China (Chengdu, Guiyang, Kunming, Chongqing, Lhasa), Northwest China (Xi'an, Lanzhou, Xining, Yinchuan, Urumqi).

Hourly concentrations of six air pollutants ($PM_{2.5}$ - particulate matter with an aerodynamic diameter of 2.5 μm or less, PM_{10} - particulate matter with an aerodynamic diameter of 10 μm or less, SO_2, NO_2, CO and O_3) were collected from the website of National Environmental Monitoring Center of China (http://113.108.142.147:20035). The daily average concentrations of these pollutants were calculated only when there was more than 16 h of valid data. The average daily maximum 8-h O_3 concentration (O_{3}_8h) was the maximum of average O_3 concentrations for 8 consecutive hours in one day.

2.1.2. Daily cause-specific mortality rate and population

The annual all-cause mortality and population in each city were obtained from the China City Statistical Yearbook 2019. The total population of 31 cities is about 243.1 million. The daily mortality was then calculated by annual mortality rate divided by the number of days per year.

2.2. Health burden assessment

The estimated health burden owing to short-term exposure to air pollutants can be calculated as follows (Silva et al. 2013; Tian et al. 2018; Xie et al., 2016):

$$M = \sum_{1}^{n} AF_i \times BM \quad (1)$$

$$AF_i = \frac{RR_i - 1}{RR_i} \quad (2)$$

$$RR_i = exp(\beta \times (C - C_0)) \quad (3)$$

Where M denotes the total mortality from air pollution, n is the total number of days, BM is the daily baseline mortality, AF_i is the daily attributable fraction associated with short-term exposure to air pollutant i. In Eq. (2), RR_i is the daily relative risk associated with short-term

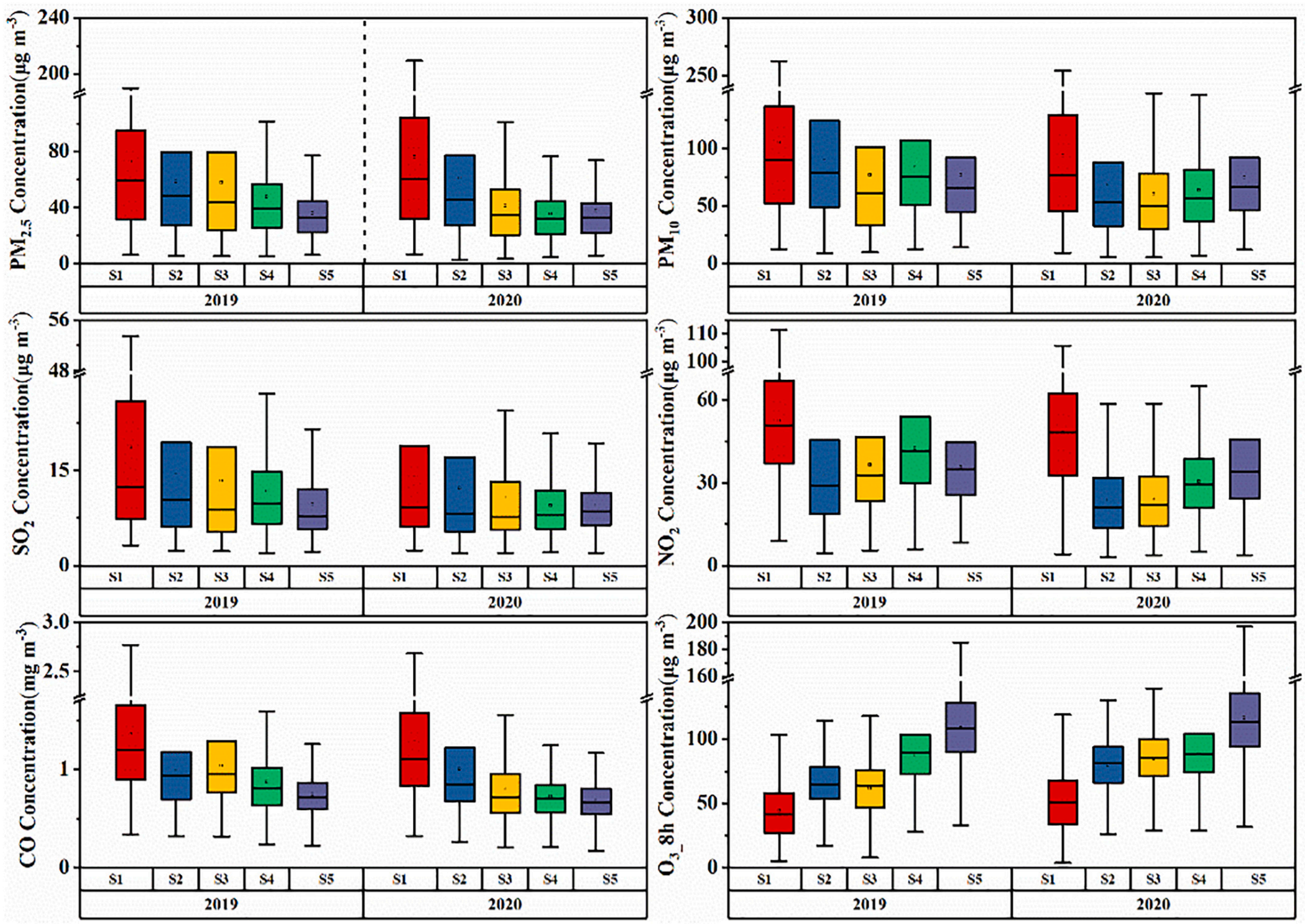

Fig. 1. The mass concentrations of air pollutants in different stages of COVID-19 pandemic in 2020 and in the same periods in 2019 (the cross symbols are mean values, the lines in the boxes are median values, the upper and lower boundaries of the boxes are 75th and 25th percentiles, and the whiskers above and below the boxes are 90th and 10th percentiles; S1-S5 represent Stages 1 to 5).

exposure to air pollutant *i*. In Eq. (3), β is the concentration-response coefficient for health endpoints exposure to air pollutants, which were obtained from recent epidemiological studies (Dong et al. 2016; Lai et al. 2013; Ma and Cui, 2016; Shang et al. 2013)(Table 1); C is the daily concentration of air pollutants; C_0 is the daily threshold concentration of air pollutants, which is assumed to be zero here similar to previous studies (Chen et al. 2017; Yao et al. 2020).

2.3. Estimation of health economic loss

The value of statistical life (VSL) method was applied to estimate the economic loss due to mortality caused by short-term exposure to air pollution. The associated health economic loss (HEL) can be calculated by:

$$HEL = M \times VSL_{k,2019} \tag{4}$$

Where M is the health burden calculated from Eq. (1). $VSL_{k,2019}$ is the adjusted VSL in city k in 2019 and can be calculated by Eq. (5) (Yao et al. 2020; Zhao et al. 2016):

$$VSL_{k,2019} = VSL_{b,2010} \times \left(\frac{G_{k,2010}}{G_{2010}}\right)^{\delta} \times (1 + \%\Delta P_k + \%\Delta \gamma_k)^{\delta} \tag{5}$$

Where $VSL_{b,2010}$ is the base value of VSL in Beijing in 2010 (1.68 million RMB). $G_{k,2010}$ is the GDP (gross domestic product) per capita in city k in 2010. G_{2010} is the GDP per capita in Beijing in 2010. δ is the income elasticity, which is assumed to be 0.8 recommended by the Organization for Economic Co-operation and Development (OECD)(OECD, 2014). $\%\Delta P_k$ represents the price inflation, i.e. percentage change in CPI (consumer price index) from 2010 to 2019; $\%\Delta\gamma_k$ is the post-2010 income growth, i.e. the percentage change of GDP per capital in city k from 2010 to 2019. The CPI and GDP data of each city are available from the China Statistical Yearbook 2019 (http://data.stats.gov.cn/easyquery.htm?cn=C01).

3. Results and discussion

3.1. Changes of air pollutants

The mean concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_{3_8h} from January 1 to May 2 in 2019 of 31 provincial capitals in China were (average ± one standard deviation) 52 ± 42, 87 ± 57, 13 ± 11, 41 ± 19, 0.97 ± 0.47, 78 ± 35 (mg m^{-3} for CO, μg m^{-3} for others), respectively. The corresponding concentrations in 2020 were 48 ± 44, 73 ± 51, 11 ± 8, 34 ± 18, 0.87 ± 0.45, 87 ± 35 (mg m^{-3} for CO, μg m^{-3} for others). Overall, except O_3, concentrations of all other pollutants decreased substantially, showing an overall improvement of air quality during COVID-19 pandemic, and indicating that the prevention and control actions had a positive effect on air quality. Nevertheless, O_3 is still a concern, and its increase is consistent with its trend in recent years (Li et al. 2019a; Liu et al. 2020; Shen et al. 2020).

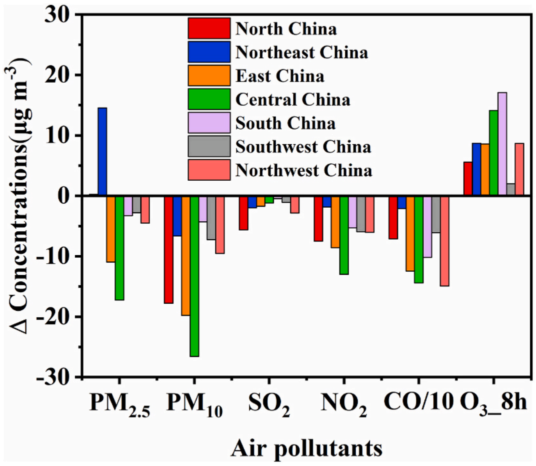

Fig. 2. The differences of concentrations of six air pollutants in seven regions between 2019 and 2020 (2020–2019).

Furthermore, Fig. 1 presents the average concentrations of six pollutants in different stages of COVID-19 pandemic and corresponding values in 2019. Influences of control measures on different pollutants are clearly diverse. In 2020, relative to Stage 1, the concentrations of $PM_{2.5}$ and CO dropped obviously in Stages 2 and 3, and then remained at a similar level in Stages 4 and 5. Similar reductions of $PM_{2.5}$ and CO concentrations in Stage 2 were observed in 2019 too, yet not in Stage 3. The drops from Stage 1 to Stage 2 found in both 2019 and 2020 were likely because Stage 2 in both years included the Spring Festival holiday therefore emission reductions can both be expected. The greater drops in Stage 3 from Stage 2 of $PM_{2.5}$ (32.8% in 2020 versus 1.7% in 2019) and CO (19.0% in 2020 versus −5.1% in 2019) were strong evidences of lockdown effects. For SO_2, the year-to-year difference between 2019 and 2020 was insignificant. The influence of lockdown on NO_2 concentration appeared to be more significant, as much bigger reductions were seen in both Stage 2 (50.0% in 2020 versus 37.7% in 2019) and Stage 3 (50.0% in 2020 versus 30.2% in 2019) relative to Stage 1. As NO_2 is mainly associated with traffic activities, such remarkable drops reflect clearly the effects lockdown on human activities. On the other hand, rebound of NO_2 level in Stages 4 and 5 relative to Stage 3 in 2020 was also obvious, indicating resumption of anthropogenic activities. This is consistent with variations of the satellite-retrieved NO_2 concentrations (Zhang et al. 2020). In addition, there were also bigger drops from Stage 1 to Stages 2 and 3 in 2020 for PM_{10} than those in 2019 (26.6% and 35.1% versus 13.3% and 26.7%), likely reflecting more reduced road/construction dust emissions due to lockdown. Rebound of PM_{10} concentration in Stages 4 and 5 was also observed, which might be associated with recovered traffic/construction activities and/or dust storms that often occur in spring. Quite differently, O_3 concentration increased significantly during Stages 2 and 3 in 2020, even more greatly than that in same periods of 2019 (53.8% and 63.5% versus 46.7% and 37.8%). This is likely attributed to abatement of NO_2 titration effect (as NO_x emissions largely decreased) (Chen et al. 2020a; Huang et al. 2020b) and the plausible feedback mechanism between $PM_{2.5}$ and O_3 (decreased $PM_{2.5}$ induced scattering effect was weakened, then likely increased the photolysis rate and promoted O_3 generation) (Feng et al. 2019) during the quarantine period.

Furthermore, the regional changes of concentrations of six pollutants between 2019 and 2020 are presented in Fig. 2. For PM_{10}, SO_2, NO_2, and CO, which are predominantly of primary origins, their concentrations all decreased in 2020, but the regional differences were remarkably large. East and North China showed relatively large reductions of PM_{10} and NO_2, while larger decrease of SO_2 was found in North and Northwest China than in other regions. CO reduction was more obvious in East, Central and Northwest China. $PM_{2.5}$ concentration decreased in most parts of China, but significantly increased in Northeast China (and North China yet in a much lesser extent). This is partially due to complicated aerosol chemistry as $PM_{2.5}$ contains both primary and secondary components therefore its response to emission change is highly non-linear (Chang et al. 2020; Huang et al. 2020b; Wang et al. 2020a; Zheng et al. 2020). O_3 concentrations increased in all regions, especially in South and Central China.

3.2. *Premature mortality attributable to air pollutants*

Based on monitoring data of six pollutants in 2019 and 2020, the all-cause premature mortality by short-term exposure to air pollution in 31 provincial capitals were calculated here. It should be noted that, we did not separate impacts of meteorology on variations of the pollutants, as well as estimates of premature deaths and associated economic loss in this work. The meteorological influence, however, is expected to be small (Pei et al. 2020). A recent study which uses a meteorology normalisation technique points out the meteorology could increase NO_2 reduction by 11% and increase the reduction of premature deaths by 6.5% in Spain during March 15 to April 23, 2020 (Achebak et al. 2020; Petetin et al. 2020). The difference in concentrations between two consecutive years should be mainly governed by emission/chemistry. In particular, our analysis was based on a national/regional average across a four-month period, the biases should be smaller.

The total premature deaths attributable to air pollution during the study period in 2019 and 2020 were 90,599 (69579–109,185) and 81,189 (62306–98,041), respectively (Table 2). Individually, the mortalities owing to $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_3 were on average 10,290, 13,162, 5151, 29,609, 17,113, 15,274, and 9267, 10,910, 4375, 24,439, 15,452, 16,746 in 2019 and 2020, respectively. NO_2 rather than particulate matter (either $PM_{2.5}$ or PM_{10}) was the largest contributor to premature deaths in both 2019 and 2020, but its contribution decreased from 32.7% in 2019 to 30.1% in 2020. Relative contributions of $PM_{2.5}$, PM_{10}, SO_2 and CO varied very little from 2019 to 2020 (all $<\pm1\%$), O_3 contribution increased substantially from 16.8% in 2019 to 20.6% in 2020.

Compared to 2019, the total avoided premature deaths in 31 provincial capitals during the COVID-19 pandemic due to air quality improvement was 9410 (7273–11,144) (Table 2). This number is about two times of the death toll of COVID-19 disease in China (4741 as of

Table 2
The premature mortality attributable to short-term exposure to air pollutants in 2019 and 2020.

Air pollutants	2019		2020		2019–2020	
	Premature deaths (person)	Contribution (%)	Premature deaths (person)	Contribution (%)	Avoided deaths (person)	Contribution (%)
$PM_{2.5}$	10,290 (8419–12,151)	11.3	9267 (7581–10,943)	11.4	1023 (838–1208)	10.9
PM_{10}	13,162 (9390–17,308)	14.5	10,910 (7777–14,359)	13.5	2252 (1613–2949)	23.9
SO_2	5151 (3443–6284)	5.7	4375 (2923–5340)	5.4	776 (520–944)	8.2
NO_2	29,609 (23437–33,672)	32.7	24,439 (19325–27,811)	30.1	5170 (4112–5861)	54.9
CO	17,113 (13380–20,767)	18.9	15,452 (12077–18,759)	19.0	1661 (1303–2008)	17.7
O_3_8h	15,274 (11510–19,003)	16.9	16,746 (12623–20,829)	20.6	−1472(−1113–1826)	−15.6
Total	90,599 (69579–109,185)	100	81,189 (62306–98,041)	100	9410 (7273–11,144)	100

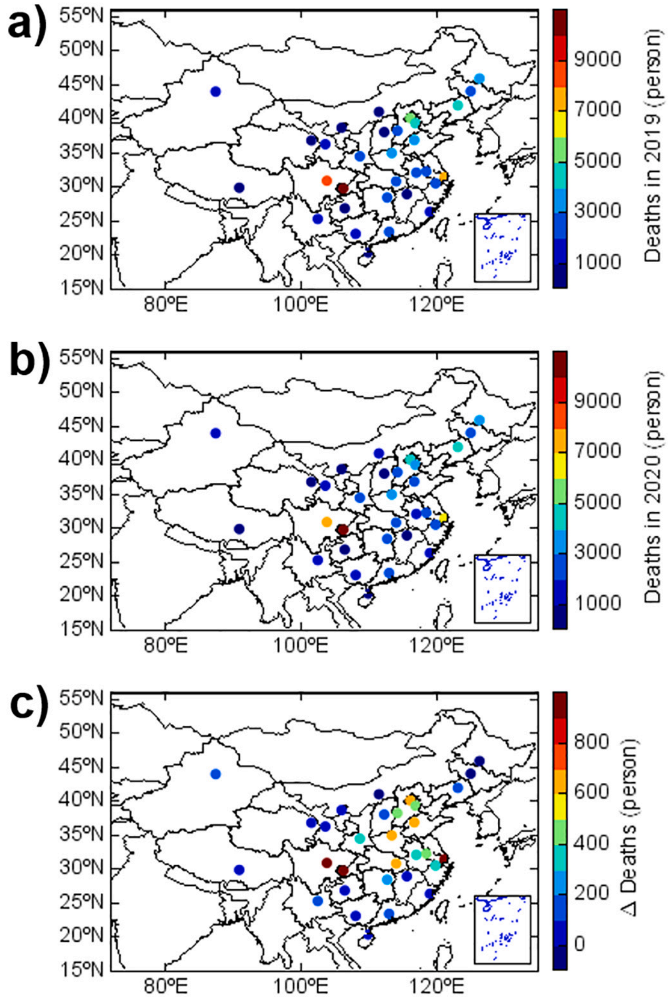

Fig. 3. The distributions of air pollution-related premature deaths: a) 2019, b) 2020, and c) difference between 2019 and 2020 (2019–2020).

September 13, 2020). The value apparently can be much larger if we include more cities as population of the 31 provincial capital cities is only ~17.4% of the total population of China. Our results quantify the health benefit from improvement of air quality due to control measures imposed during COVID-19 pandemic in China. Such potential benefits in China were proposed recently (Chen et al. 2020b; He et al. 2020), and might exist in other countries as well (Han and Hong 2020). In details, the average avoided premature deaths from $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3 were 1023, 2252, 776, 5170, 1661, −1472, respectively. Note the avoided mortality from NO_2 reduction was largest (54.9% of total), followed by PM_{10} (23.9%), CO (17.7%), $PM_{2.5}$ (10.9%) and SO_2 (8.2%). NO_2 alone could compensate the death loss of COVID-19 in China. However, corresponding increase of O_3, closely associated with NO_2 reduction, on the contrary could cause more premature deaths (−15.6% of total), indicating the complexity and importance of O_3 control in future.

We chose the mean value as the best estimate and presented its spatial distributions in Fig. 3. Large and unequal distribution in different regions can be observed. The top four cities with positive health benefits were Chongqing, Chengdu, Shanghai and Beijing (Fig. 3c). Note these cities were also the top four cities with high air pollution related premature deaths in both 2019 and 2020 (Fig. 3a and b). Three cities, Hohhot, Changchun and Harbin, were found to have negative numbers of avoided deaths, i.e., the air pollution during COVID-19 pandemic aggravated the deaths. This was mainly owing to increases of both $PM_{2.5}$ and O_3 in these cities (Fig. 2).

We further investigated the daily average premature deaths in different stages and regions during the pandemic in Fig. 4. In Fig. 4a, clear declines in 2020 were found in Stages 1–4 while negligible increase (<0.3%) was found in Stage 5. The reduction in Stage 1 was 7.7% (Fig. 1). Possibly, although no lockdown measures were imposed in Stage 1, in the last few days of this period, anthropogenic emissions might become less than those of 2019 as a lot of people left the capital cities for Spring Festival. Nevertheless, reduction rates in Stages 2–4 (15.1%, 15.9% and 20.0%) were apparently larger than that of Stage 1, pointing to the health benefits from reduced air pollution due to COVID-19 control measures. Fig. 4b shows further the daily average avoided mortalities per city in the seven regions for each stage. Large diversity was found in different regions during the same stage. During Stage 2, the value in Southwest China was largest, while in Stages 3 and 4, Northeast China was the largest. However, the large positive effect in Northeast China in Stages 3 and 4 was offset by the negative effects in Stages 1, 2 and 5, and overall, Northeast China had a small negative avoided premature mortality.

Fig. 4c shows the daily avoided premature deaths from individual pollutants and their total. It can be seen that for the same pollutant, the daily values changed greatly among different stages. Contributions from $PM_{2.5}$ and NO_2 reductions were largest in Stage 4, PM_{10} contributed the most in Stage 2, and CO contributed the most in Stage 3, while SO_2 contribution during control periods (Stages 2–4) was not obvious, less than that during Stage 1. In Stage 5, CO could avoid premature deaths (influences of $PM_{2.5}$, PM_{10}, SO_2 and NO_2 were all very small), but it was almost offset by the negative effect from O_3. In total, there was a small negative number in Stage 5 (−2 per day), but large positive values were found for Stages 1–4, and those in Stages 2–4 were much larger (last column in Fig. 4c). The stage with largest avoided premature mortality was Stage 4 (150 per day) rather than Stages 2 (~106 per day) and 3 (~109 per day) when stricter control measures were imposed. The reason is that Stage 4 had the largest reduction of NO_2 (corresponding to largest avoided daily mortality) but smallest increase of O_3 (corresponding to lowest increased daily mortality) among all stages (Figs. 1 and 4b). Last, Fig. 4d shows the average daily avoided deaths per city from each pollutant in seven regions. Southwest, Central, Southwest and East China appeared to be top three regions of avoided premature mortality, mainly due to contributions from NO_2, $PM_{2.5}$, PM_{10}, and CO. Again, as already demonstrated in Fig. 2, capital cities in Northeast China had negative health benefits due to mainly $PM_{2.5}$ and O_3 increases.

3.3. Health economic loss attributable to air pollutants

The summed economic losses due to air pollution related premature deaths in 2019 and 2020 of the 31 provincial capitals were estimated to be 174.6 (134.2–210.3) and 155.2 (119.2–187.4) billion RMB, respectively (Table 3). Taking the averages, contributions of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, O_3 were 11.3% (19.7 billion), 14.2% (24.8 billion), 5.3% (9.2 billion), 33.4% (58.3 billion), 18.6% (32.4 billion), 17.3% (30.3 billion) in 2019, and 11.2% (17.4 billion), 13.0% (20.2 billion), 5.0% (7.7 billion), 30.6% (47.5 billion), 18.9% (29.3 billion), 21.4% (33.2 billion) in 2020, respectively. Similar to the heath burden, NO_2 was again the largest contributor, but its contribution decreased in 2020 due to remarkable reduction.

The total avoided health economic loss was 19.4 (15.0–23.0) billion, contributed by 2.3 billion from $PM_{2.5}$, 4.6 billion from PM_{10}, 1.5 billion from SO_2, 10.8 billion from NO_2, 3.1 billion from CO, and −2.9 billion from O_3 (Table 3). Again, opposite to other pollutants, O_3 increase led to more economic loss than that of 2019. The spatial distributions of economic losses (average values) in 2019 and 2020, as well as the differences of 31 cities were shown in Fig. 5. The top four cities were Chongqing, Shanghai, Beijing and Chengdu. This was slightly different from ones of air pollution related premature deaths, as the economic

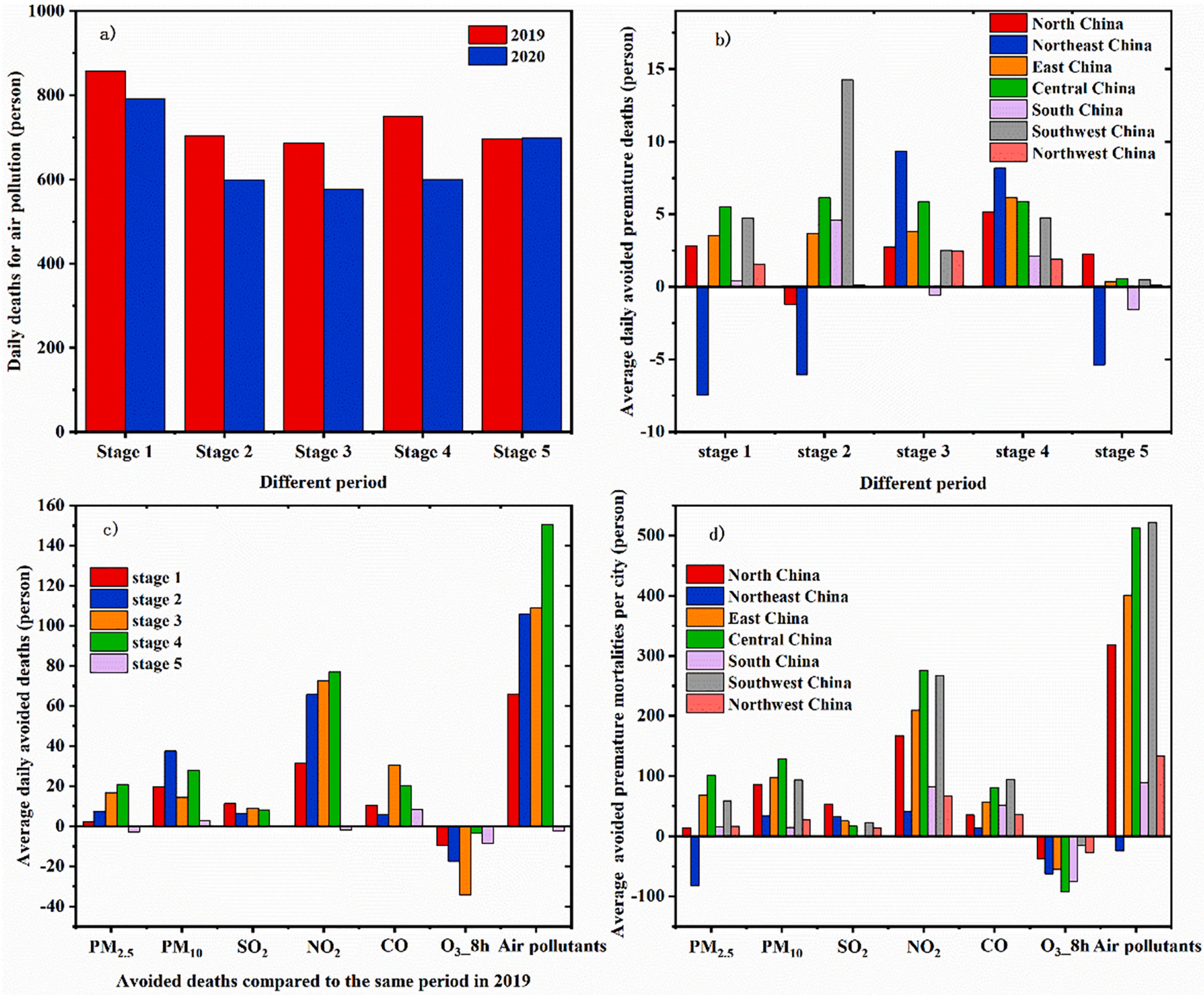

Fig. 4. The avoided premature mortalities attributed to short-term air pollutant exposure: a) average daily premature mortalities in different periods; b) average daily avoided premature mortalities in seven regions in different periods; c) average daily avoided premature mortalities attributable to different pollutants in different periods; d) average daily avoided premature mortalities attributable to different pollutants in seven regions.

Table 3
The health economic loss (in RMB) attributable to air pollutants in 2019 and 2020.

Air pollutants	2019		2020		2019–2020	
	Economic loss (billion)	Contribution (%)	Economic loss (billion)	Contribution (%)	Avoided Loss (billion)	Contribution (%)
$PM_{2.5}$	19.7 (16.1–23.2)	11.3	17.4 (14.2–20.5)	11.2	2.3 (1.9–2.7)	11.8
PM_{10}	24.8 (17.7–32.6)	14.2	20.2 (14.4–26.5)	13	4.6 (3.3–6)	23.8
SO_2	9.2 (6.1–11.2)	5.2	7.7 (5.1–9.4)	4.9	1.5 (1–1.8)	7.6
NO_2	58.3 (46.2–66.3)	33.4	47.5 (37.6–54.1)	30.6	10.8 (8.6–12.3)	55.8
CO	32.4 (25.3–39.4)	18.6	29.3 (22.9–35.6)	18.9	3.1 (2.4–3.8)	16.0
O_3_8h	30.3 (22.8–37.7)	17.3	33.2 (25–41.3)	21.4	−2.9 (−2.2–3.6)	−15.0
Total	174.7 (134.2–210.4)	100	155.3 (119.2–187.4)	100	19.4 (15.0–23.0)	100

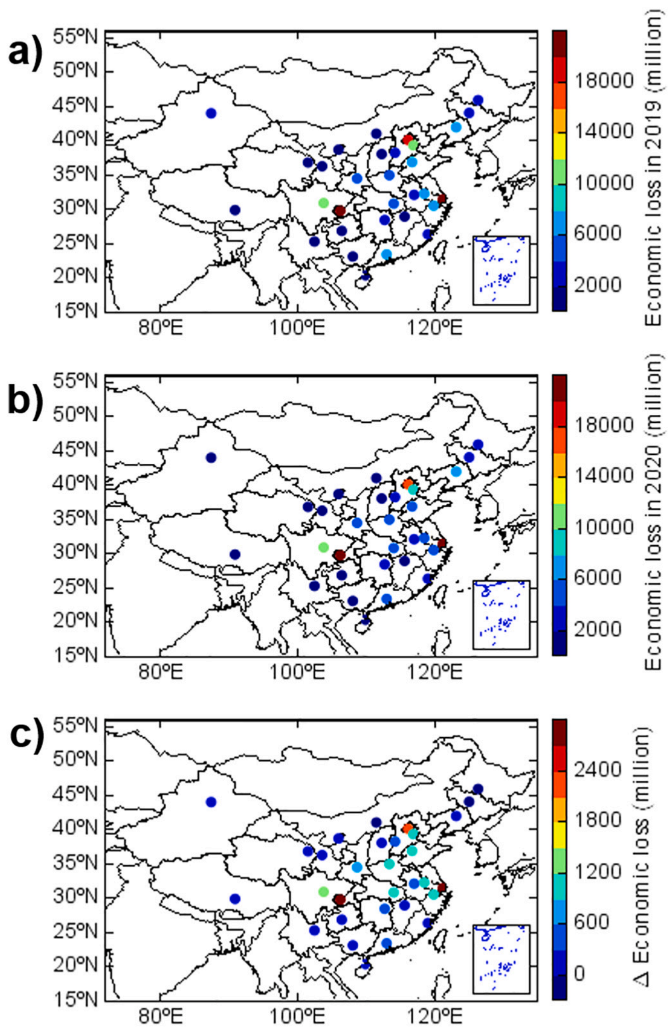

Fig. 5. The distributions of air pollution-related health economic loss: a) 2019, b) 2020, and c) difference between 2019 and 2020 (2019–2020).

expense also depends on the willingness to pay to prevent death, which again is closely relevant with the economic level of that city. The avoided economic losses in Hohhot, Changchun and Harbin were negative, implying these cities suffered a dual economic loss from both work shutdown and deteriorated air pollution during COVID-19 pandemic.

Fig. 6a shows the daily health economic loss from air pollution in 2019 and 2020. Similar characteristic in Stages 1–4 as that shown in Fig. 4a was found, namely, more significant reductions in Stages 2–4 than that in Stage 1. However, in contrast to the small negative health benefit, a small positive economic benefit was found in Stage 5. Correspondingly, Fig. 6b presents detailed contributions of seven regions to the avoided health economic loss in each stage. The results were also similar to that in Fig. 4b, except that values in East and North China were higher than that in Northeast China. Fig. 6c and d display the average daily avoided health economic loss from different stages and different regions for each pollutant, respectively. For Fig. 6c, the variability was generally similar to that of premature deaths shown in Fig. 4c, except that the avoided loss was a bit higher in Stage 2 than in Stage 3, and Stage 5 also had a positive avoided loss. The results in Fig. 6a–c together demonstrate that the willingness to pay (WTP) for reducing risk of premature death in different cities were different, which could amplify the inequalities of health economic loss. Such influence of WTP on economic loss can be clearly seen in Fig. 6d. Compared with Fig. 4d, East China became the region with largest daily avoided economic loss. This is because cities in this region are overall more developed, therefore the WTP to avoid premature mortality is higher than other regions, even though the number of its avoided premature deaths is not the largest. Except East China, variety of other regions is similar to that of premature mortality too.

3.4. Uncertainties and limitations

Our estimates here should be interpreted with caution as we did not separate meteorological influences on the air pollutants, and the concentration-response relationship of exposure to air pollutants had its own uncertainty. We provide here reasonable estimates of the air pollution-related avoided premature deaths and associated economic loss that would have occurred during the first four months of 2020, if there were no interventions to contain COVID-19. This work does not in any way intend to support the positive effect of COVID-19 to the human society. And, in fact, the estimated health and economic benefits during COVID-19 pandemic attributable to air quality improvement are far below the great expense in many aspects that China had paid during the pandemic.

4. Conclusions

We provided a timely evaluation of the health burden and economic loss attributable to short-term exposure to air pollutants during the COVID-19 pandemic period (January 1 to May 2, 2020) in 31 provincial capital cities in China. Relative to the same period in 2019, we found an overall improvement of air quality, and such improvement could avoid premature deaths of 9410 (7273–11,144) and economic loss of 19.4 (15.0–23.0) billion. NO_2 reduction was the largest contributor (~55%) rather than PM. O_3 was a negative factor to both health and economic benefits. The estimated values in different stages of the pandemic and in different regions also varied greatly. The largest health and economic benefits were actually found in February 25–March 31, the period with mild control measures, mainly due to large reduction of NO_2 yet small increase of O_3 relative to the same period of 2019. Southwest and Central China seemed to have relative larger avoided premature mortalities, while East China had the largest avoided health economic loss, due to differences of willingness to pay to reduce risks of premature deaths among different regions. Moreover, in some cities in Northeast China, air quality was not improved even during the strict quarantine period (January 25-Februray 9, 2020), and the overall health burden and economic loss changed little (small negative health effect and small positive economic effect) compared to 2019.

Our results also showed though with the larger emission reductions during COVID-19 lockdown, some air pollutants (such as O_3) still increased, suggesting the multi-pollutant control strategies are needed. Overall health and economic benefits attributable to air pollutants could be found in China during COVID-19 lockdown, but still there was no improvement in some regions (such as Northeast China), suggesting regional-specific measures are needed. In summary, our findings here quantitatively assess the effects of short-term strict control measures on air quality as well as its associated short-term health and economic burdens, and such information is beneficial to future air pollution remediation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

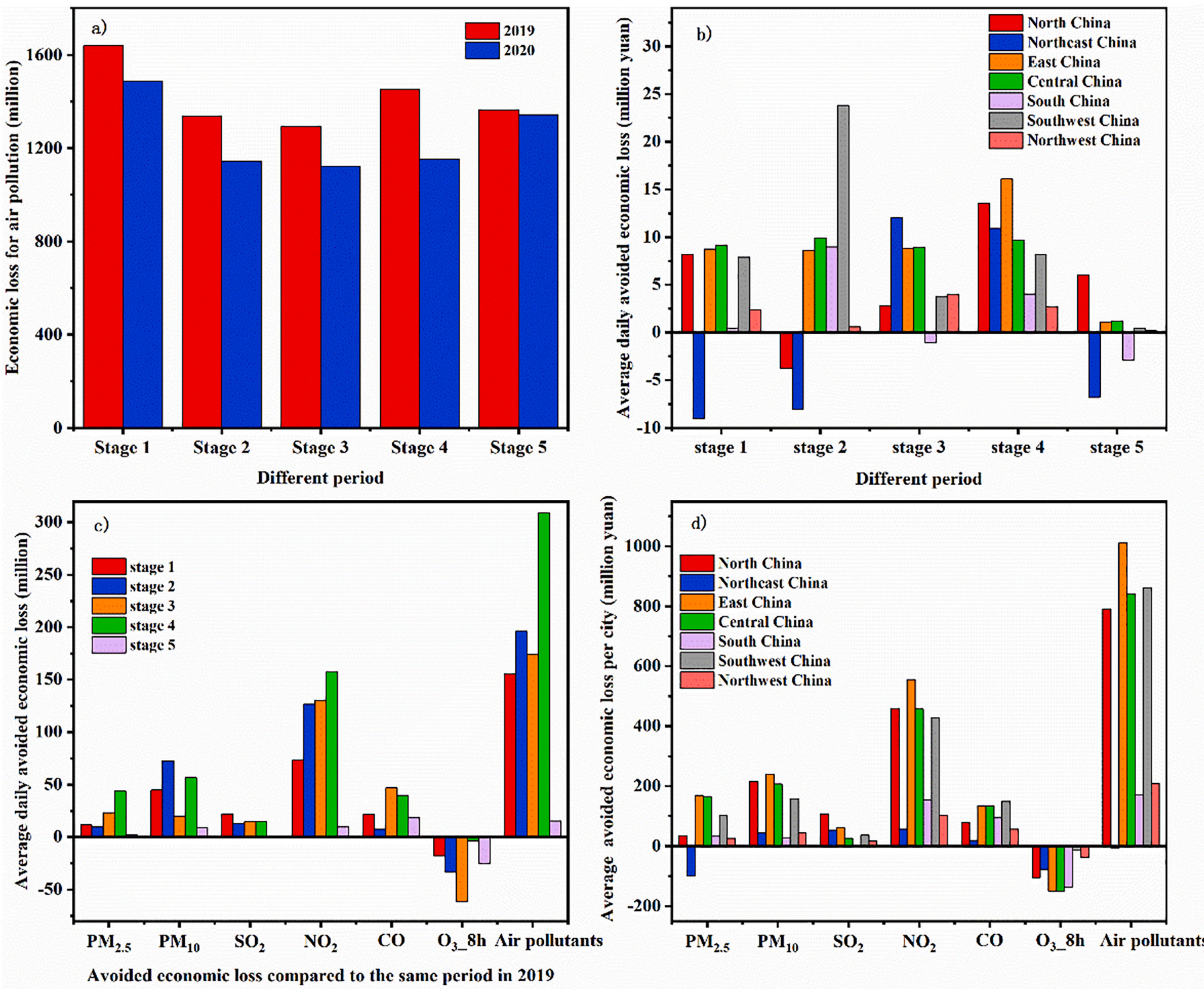

Fig. 6. The avoided economic loss attributed to short-term air pollutant exposure: a) average daily economic loss in different periods; b) average daily avoided economic loss in seven regions in different periods; c) average daily avoided economic loss attributable to different pollutants in different periods; d) average daily avoided economic loss attributable to different pollutants in seven regions.

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