SCIENTIFIC REPORTS
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Temporal variations in ambient air quality indicators in Shanghai municipality, China

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Official data on daily $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and maximum 8-h average O_3 (O_3_8h) concentrations from January 2015 to December 2018 were evaluated and air pollution status and dynamics in Shanghai municipality were examined. Factors affecting air quality, including meteorological factors and socio-economic indicators, were analyzed. The main findings were that: (1) Overall air quality status in Shanghai municipality has improved and number of days meeting 'Chinese ambient air quality standards' (CAAQS) Grade II has increased. (2) The most frequent major pollutant in Shanghai municipality is O_3 (which exceeded the standard on 110 days in 2015, 84 days in 2016, 126 days in 2017, 113 days in 2018), followed by $PM_{2.5}$ (120days in 2015, 104 days in 2016, 67 days in 2017, 61 days in 2018) and NO_2 (50 days in 2015, 67 days in 2016, 79 days in 2017, 63 days in 2018). (3) $PM_{2.5}$ pollution in winter and O_3 pollution in summer are the main air quality challenges in Shanghai municipality. (4) Statistical analysis suggested that $PM_{2.5}$, PM_{10}, SO_2 and NO_2 concentrations were significantly negatively associated with precipitation (Prec) and atmosphere temperature (T) ($p < 0.05$), while the O_3 concentration was significantly positively associated with Prec and T ($p < 0.05$). Lower accumulation of PM, SO_2, NO_2, and CO and more serious O_3 pollution were revealed during months with higher temperature and more precipitation in Shanghai. The correlation between the socio-economic factors and the air pollutants suggest that further rigorous measures are needed to control $PM_{2.5}$ and that further studies are needed to identify O_3 formation mechanisms and control strategies. The results provide scientific insights into meteorological factors and socio-economic indicators influencing air pollution in Shanghai.

China's reforms and opening-up policies since 1970s have contributed to rapid economic growth, industrialization, and urbanization[1,2], as evidenced by increased gross domestic product (GDP), urban population, and energy consumption[1,3,4]. However, this has resulted in high levels of environmental degradation[1,5,6] and associated health effects[2,6]. Air pollution in China is mainly caused by coal combustion, motor vehicles, industrial dust, chemical conversion in the atmosphere in urban centers, and unfavorable meteorological conditions, all of which are linked to rapid socioeconomic development[1,3,7,8]. With an increasing number of Chinese cities suffering from serious air pollution problems in recent decades[1,2,9], air pollution has become one of the top environmental concerns in China[1,6,9–13]. Serious air pollution hinders economic development[14] and deteriorates people's quality of life, with increasing reports of negative health risks[6,15]. Many epidemiological studies have shown that air pollution has strong associations with impaired human health[16] and mortality[14,16,17]. A recent study found that a 10 μg m^{-3} increase in particulate matter (PM_{10}) reduced life expectancy in China by 0.64 years[18]. Other studies in China have estimated that a 10 μg m^{-3} increase in PM_{10} led to a 0.44% increase in daily number of deaths[19], that $PM_{2.5}$ accounted for 15.5% (1.7 million) of all-cause deaths in China in 2015[20], and that 2.19 million (2013), 1.94 million (2014), and 1.65 million (2015) premature deaths could be attributed to long-term exposure to $PM_{2.5}$[21]. However,

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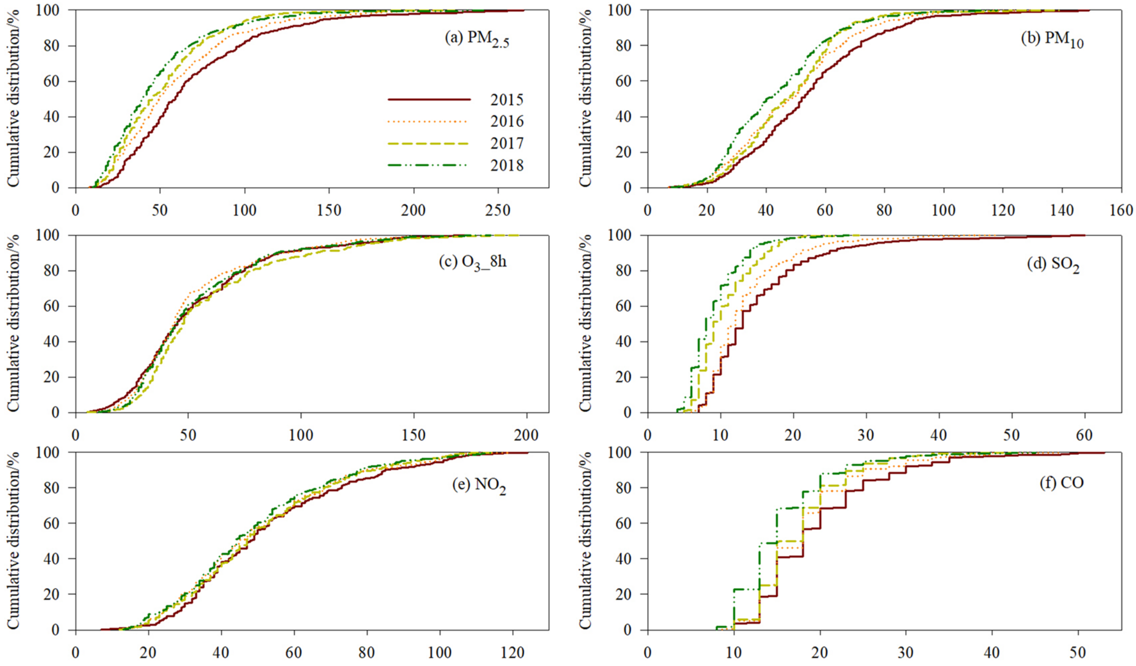

Figure 1. (**a**–**f**) Cumulative distribution of daily average mean concentrations of air pollutants in Shanghai municipality.

a recent study estimated that the number of premature deaths in China attributable to $PM_{2.5}$ has decreased by 12.6%, from 1.20 million in 2013 to 1.05 million in 2017[22].

With the growing need for improving air quality across cities, municipalities, and provinces in China, a series of laws, regulations, standards and control measures have been formulated and promulgated[1,2,4,8,23]. The 'Air Pollution Prevention Action Plan' was enacted on September 10, 2013, and the most stringent environmental protection law to date was implemented on January 1, 2015[8]. Significant measures have also been taken to mitigate the adverse effects of air pollution[24]. Air quality monitoring systems have been established in more than 330 cities[16] and at 1,300 national air quality monitoring sites[24]. Daily data on air quality index (AQI) and air quality indicators are released publicly on local government websites, providing an important foundation for air quality research and policy. In the past three decades, knowledge on air pollution has improved considerably with the growing number of publications on air pollution in megacities[2,4,8,14,16,22,24,25]. Many studies have reported spatio-temporal variations in particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous (SO_2, NO_2, CO, and O_3) pollutants in Chinese cities[4,8,16,24,26], and associated health and socioeconomic costs[3,6,14,21,22,27–29]. Between 2013 and 2018, China's rigorous air pollution control greatly reduced the annual mean level of $PM_{2.5}$ in the atmosphere of 74 large cities[30].

Shanghai is an important political, economic, and cultural center of China. With the acceleration of urbanization and industrial processes, Shanghai's environmental problems have become increasingly prominent, with air quality being one of the most serious issues. As a pioneer city in construction of ecological civilization, Shanghai's air quality has received much attention. In this study, official data on daily concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and maximum 8-h average concentration of O_3 (O_3_8h) in the air in Shanghai municipality from January 2015 to December 2018 were used to examine air pollution status and dynamics in the municipality. The following aspects are addressed in this paper: (1) Temporal variations in average daily concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3_8h in the air in Shanghai municipality during 2015–2018; (2) annual and seasonal variations in major pollutants and number of days when concentrations exceeded the air quality standard; and (3) the main meteorological factors and socio-economic indicators affecting air pollution in Shanghai. The results were used to identify air quality management gaps in the municipality.

Results and discussion

Overview of air pollutants in Shanghai during 2015–2018.

The average mass concentrations of the target pollutants during 2015–2018 were analyzed. We used the cumulative distribution of daily average values of $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3_8h to determine the number of days during which Shanghai municipality was exposed to air pollution (Fig. 1)[24]. For at least some half-days in 2015 (2016, 2017, 2018), Shanghai municipality was exposed to average values higher than 59 (50, 45, 40) μg m^{-3} for $PM_{2.5}$, 52 (48, 47, 40) μg m^{-3} for PM_{10}, 45 (43, 47, 44) μg m^{-3} for O_3_8h, 48 (45, 47, 44) μg m^{-3} for NO_2, 13 (12, 9, 8) μg m^{-3} for SO_2, and 18 (18, 18, 15) mg m^{-3} for CO. This indicates a decrease in the number of days per year in which Shanghai residents were exposed to high concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO.

Temporal variations in air pollutants.

Following implementation of the six-round, 3-year environmental protection action plan, ambient air quality in Shanghai municipality has improved slightly. In 2018, the aver-

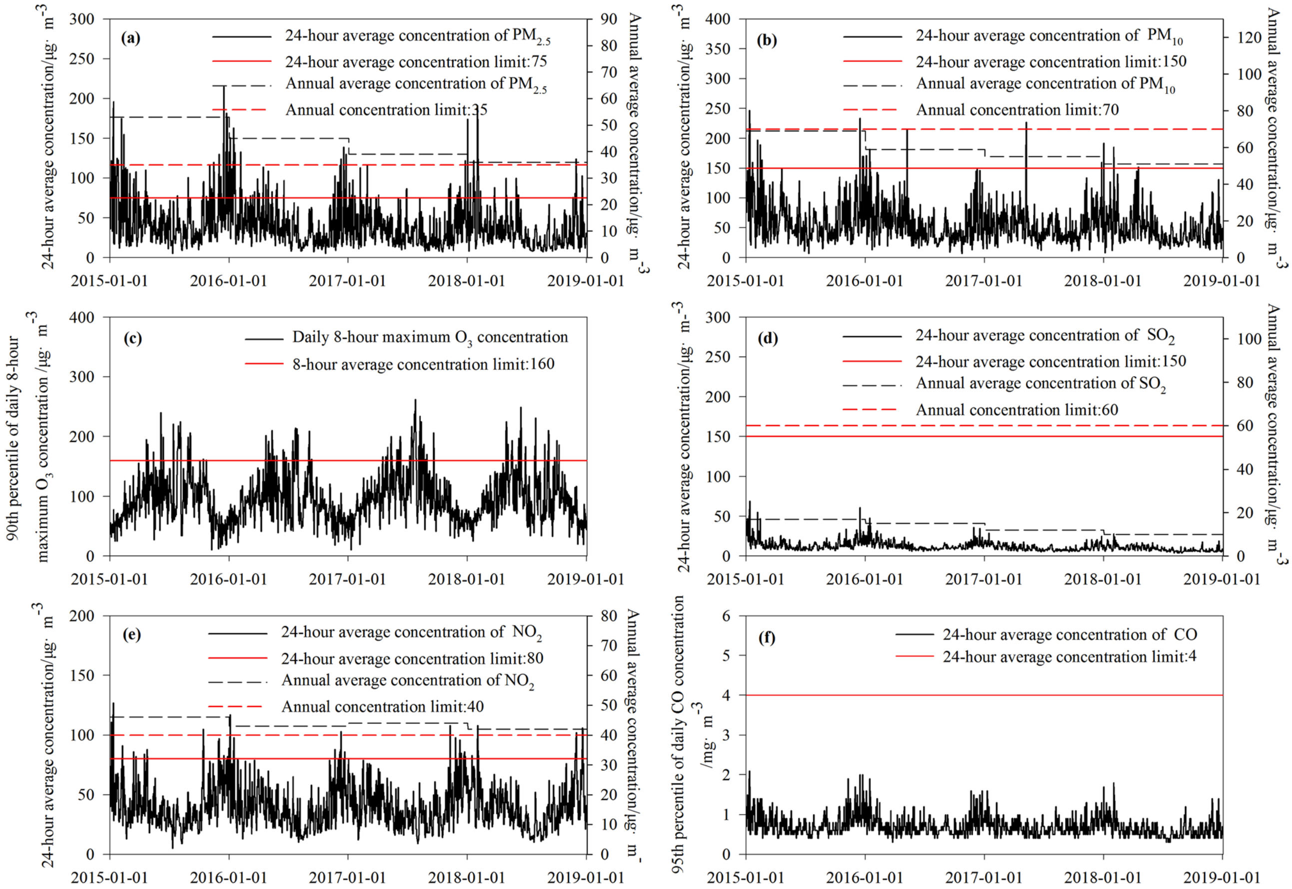

Figure 2. Temporal variations in 24-h average concentrations and annual mean concentrations of air pollutants in Shanghai municipality, 2015–2018.

age annual concentration of SO_2 and PM_{10} in Shanghai municipality was 10 μg m^{-3} and 51 μg m^{-3} respectively, the 90th percentile of O_3_8h concentration was 160 μg m^{-3}, and daily CO concentration was within the range 0.4–2.0 mg m^{-3}. All these concentrations met the national Level I or Level II for annual mean ambient air quality. However, the average annual concentration of NO_2 and $PM_{2.5}$ in the city in 2018 was 42 μg m^{-3} and 36 μg m^{-3}, respectively, which did not meet the Level II annual mean level air quality standard. Moreover, monitoring data for the past 4 years show that the annual mean concentrations of NO_2 and $PM_{2.5}$ in Shanghai are generally declining, but they still exceed the national Level II air quality standards. The daily maximum 8-h average, 24-h average, and annual mean concentrations of six air pollutants in Shanghai municipality during 2015–2018 are summarized in Fig. 2. Compared with 2015, the average concentration in 2018 decreased by 32.08%, 26.09%, 0.62%, 41.18%, 8.70%, and 22.09% for $PM_{2.5}$, PM_{10}, O_3_8h, SO_2, NO_2, and CO, respectively. The large decrease in SO_2 in the air Shanghai municipality was consistent with the overall trend in annual mean concentration of SO_2 in China[8]. This indicates effective control of combustion emissions and implementation of desulfurization systems[8,31]. Our results also indicated that more than 70% of the total mass of PM_{10} was composed of $PM_{2.5}$, which is close to the ratio reported in previous studies[8,24]. The decreases in CO and NO_2 concentrations were mainly attributable to effective regulation of coal combustion emissions and traffic-related emissions[8,31–33]. The reductions amplitudes were lower for CO and NO_2 compared with $PM_{2.5}$, PM_{10}, and SO_2, which may be related to the rapid increase in vehicles in Chinese cities[8]. No clear decrease was observed for the 90th percentile of O_3_8h concentration in this study. Air pollution has gradually changed from the conventional coal combustion type to mixed coal combustion/motor vehicle emission type[3], reflecting the rapid increase in the number of motor vehicles in Shanghai municipality[34]. This poses enormous challenges for air pollution control and environmental management.

Major pollutants and non-attainment days. The number of days meeting the mean concentration limits of 'Chinese ambient air quality standards' (CAAQS) in Shanghai municipality during 2015–2018 was examined (Fig. 3). In 2015 (2016, 2017, 2018), 18.6% (27.5%, 33.6%, 41.5%), 77.9% (85.3%, 92.6%, 91.5%), 35.8% (40.1%, 35.2%, 41.0%), 99.5% (100%, 100%,100%), 99.7 (100%, 100%, 100%), and 58.4% (67.2%, 57.0%, 60.8%) of days met the concentration limit in CAAQS Grade II for 24-h average $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and maximum 8-h average O_3. Compared with 2015, the number of days in 2018 that met the level in CAAQS Grade II increased by 124.3%, 17.5%, 4.1%, 14.5%, 0.5%, and 0.3% for $PM_{2.5}$, PM_{10}, O_3_8h, SO_2, NO_2, and CO, respec-

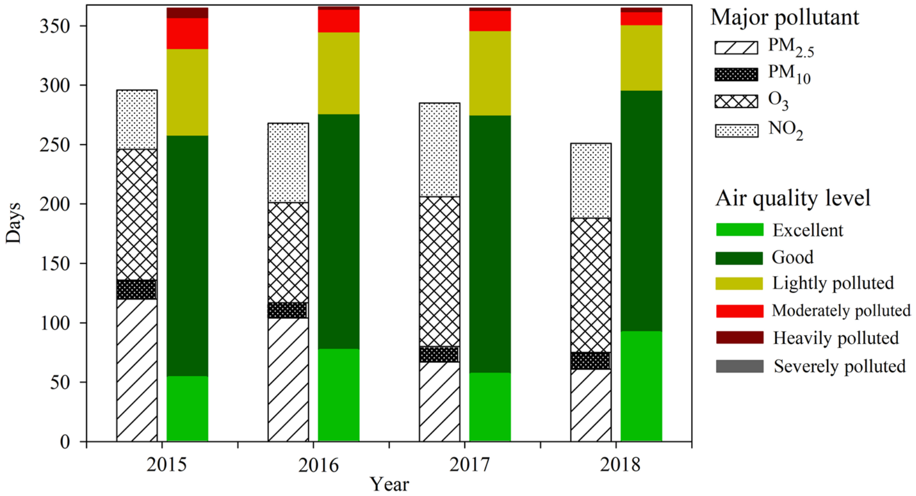

Figure 3. Number of days per year on which each pollutant was designated a "major pollutant" (different shapes) and air quality level (different colors) in Shanghai municipality.

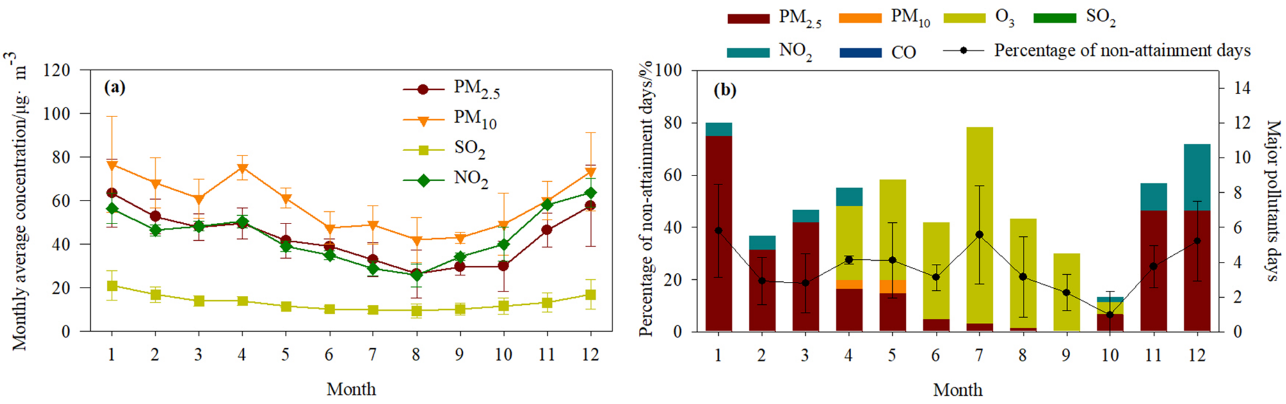

Figure 4. (**a**) Average concentration of the pollutants $PM_{2.5}$, PM_{10}, SO_2, and NO_2 and (**b**) percentage of non-attainment days and major pollutant on polluted days in each month during 2015–2018.

tively. The number of days with excellent air quality increased from 55 in 2015 to 93 in 2018, while the number of days with 'good' air quality remained consistent at 203 days between 2015 and 2018.

The most frequent "major pollutant" in Shanghai municipality was O_3, followed by $PM_{2.5}$ and then NO_2 and PM_{10}. In comparison, SO_2 and CO were the "major pollutant" considerably less frequently. The number of days on which $PM_{2.5}$, O_3, NO_2, and PM_{10} was designated the "major pollutant" was 120 (104, 67, 61), 110 (84, 126, 113), 50 (67, 79, 63) and 16 (13, 13, 14) in 2015 (2016, 2017, 2018), respectively. The low incidence of SO_2 as a "major pollutant" again indicated effective control of coal combustion and implementation of desulphurization systems[8,31]. Compared with 2015, the incidence of O_3 as a major pollutant in Shanghai increased to reach its highest value in 2017. This is consistent with the 90th percentile of O_3_8h concentration, which also peaked in 2017. Previous studies have suggested that O_3 is a complex secondary pollutant related to solar radiation, NO_x, volatile organic compounds (VOC), and vertical transport in the boundary layer[8], factors that are difficult to control effectively[35,36]. While the number of polluted days with $PM_{2.5}$ concentrations over 75 μg m^{-3} decreased from 2015 to 2018, the complex mixture of $PM_{2.5}$ and O_3 in the air is still a challenge to continuous improvement of air quality in Shanghai municipality[8,24].

There were seasonal variations in the concentrations of each pollutant (Fig. 4a), and thus the days on which the air quality standard was exceeded (non-attainment days) were not equally distributed throughout the year (Fig. 4b), which is consistent with findings in previous studies[24,37]. November, December, January, February, and March were the dominant months with non-attainment days for $PM_{2.5}$ in Shanghai municipality, while April, May, June, July, August, and September were the dominant months with non-attainment days for O_3_8h. Overall, winter months had the largest number of polluted days and highest mean concentration of $PM_{2.5}$, followed by spring, autumn, and summer, which is consistent with previous findings[16]. This trend has been mainly attributed to coal-fired heating of buildings[16,38–40]. Summertime O_3 pollution in Shanghai was much more severe than in the other seasons (Fig. 4b), and the probability of O_3_8h exceeding the CAAQS Grade II value was highest in July (11.25 ± 5.85 day), followed by August (6.25 ± 4.65 day), May (5.75 ± 3.2 day), and June (5.5 ± 1.29 day). This is consistent with findings in previous studies that summer is the O_3 episode season in Chinese megacity

	PM_{10}	O_3	SO_2	NO_2	CO
$PM_{2.5}$	0.879**	0.093**	0.708**	0.693**	0.817**
PM_{10}		0.172**	0.739**	0.632**	0.686**
O_3			− 0.026	− 0.206**	− 0.128**
SO_2				0.602**	0.633**
NO_2					0.706**

Table 1. Correlations between pollutants based on daily data for Shanghai during 2015–2018 ($^{**}p<0.01$; $^{*}p<0.05$).

	W	*T*	*RH*	$PM_{2.5}$	PM_{10}	O_3	SO_2	NO_2	CO
Prec	− 0.093	0.532**	0.765**	− 0.353*	− 0.435**	0.342*	− 0.459**	− 0.429**	− 0.289*
W		− 0.205	− 0.222	− 0.056	0.033	− 0.072	0.125	− 0.154	− 0.212
T			0.416**	− 0.77**	− 0.674**	0.735**	− 0.703**	− 0.839**	− 0.67**
RH			1	− 0.252	− 0.472**	− 0.015	− 0.403**	− 0.293*	− 0.185

Table 2. Correlations between air pollutants and meteorological factors based on the monthly data for Shanghai during 2015–2018. *Prec*: precipitation; *W*: wind speed in two minutes; *T*: temperature; *RH*: relative air humidity. $^{**}p<0.01$; $^{*}p<0.05$.

clusters[41,42]. Polluted days with $NO_2 > 80$ μg m^{-3} were mainly observed during winter and spring. The low probability of SO_2 exceeding the CAAQS Grade II value reflected the stringent SO_2 emission regulations in Shanghai municipality[31].

Correlations between air pollutants. Different air pollutants were significantly correlated ($p<0.01$) with each other, except for SO_2 and O_3 (Table 1). There were significant positive correlations between $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2, suggesting that these pollutants originated from the same sources (e.g., vehicle and coal emissions) or were impacted by the same drivers[24]. Therefore controlling traffic and coal combustion emissions might be a way of simultaneously decreasing the concentrations of these pollutants. O_3 was significantly positively correlated with PM, and negatively correlated with NO_2 and CO ($p<0.01$). The correlation coefficients were weaker, however, which can mainly be attributed to the complex, nonlinear, and temperature-dependent chemistry of O_3 concentration[20,43]. This indicates difficulty in controlling O_3 concentration and merits further investigations on O_3 formation and control strategies in Shanghai municipality.

Correlations between air pollutants and meteorological factors. Correlations between the six main pollutants and meteorological factors are shown in Table 2. The results suggested that temperature (*T*) significantly impacted accumulation of all six pollutants in Shanghai municipality, while precipitation (*Prec*) and relative air humidity (*RH*) may have affected accumulation of some pollutants. Of all the meteorological factors that significantly impacted pollutant concentrations, the correlations between meteorological factors and $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 were negative, while the correlations between meteorological factors and O_3 were positive.

The concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO displayed a significantly negative relationship with *Prec* ($p<0.05$ or $p<0.01$), suggesting that the wet deposition could mitigate air pollution by the scavenge and wash-out process[16,44,45]. Relative humidity was strongly positively correlated with *Prec*, leading consistently to significantly negative correlations between PM_{10}, SO_2 and NO_2 and *RH*. The consistency in correlations between the pollutants and *T*, and that between the pollutants and *Prec*, was partly explained by the significantly positive correlation between *Prec* and *T*. This also explains why the average concentration of the pollutants $PM_{2.5}$, PM_{10}, SO_2, and NO_2 during June–September was lower than in other months[46,47]. Wind speed (*W*) did not show any marked relationship with the air pollutants studied, indicating that *W* did not enhance air ventilation and turbulence and thus improve air quality.

Correlations between air pollutants and socio-economic indicators. Shanghai is undergoing strong socioeconomic development, with the permanent resident population (PRP) increasing from 14.14 million in 1995 to 24.18 million in 2017, and the GDP of Shanghai municipality increasing from 251.8 billion RMB in 1995 to 3,063.2 billion RMB in 2017[34] (Fig. 5). In the same period, Shanghai municipality continuously increased its environmental protection and construction efforts, with rolling implementation of the six-round, 3-year environmental protection action plan. Green space area (GE) has increased, from 6,561 hm^2 in 1995 to 136,327 hm^2 in 2017, environmental investment (EI) has also increased, from 4.65 billion RMB in 1995 to 92.35 billion RMB in 2017, and total amount of smoke emissions (SE) and total exhaust sulfur dioxide emissions (SDE) has decreased from 207.8 thousand tons and 534.1 thousand tons, respectively, in 1995 to 47 thousand

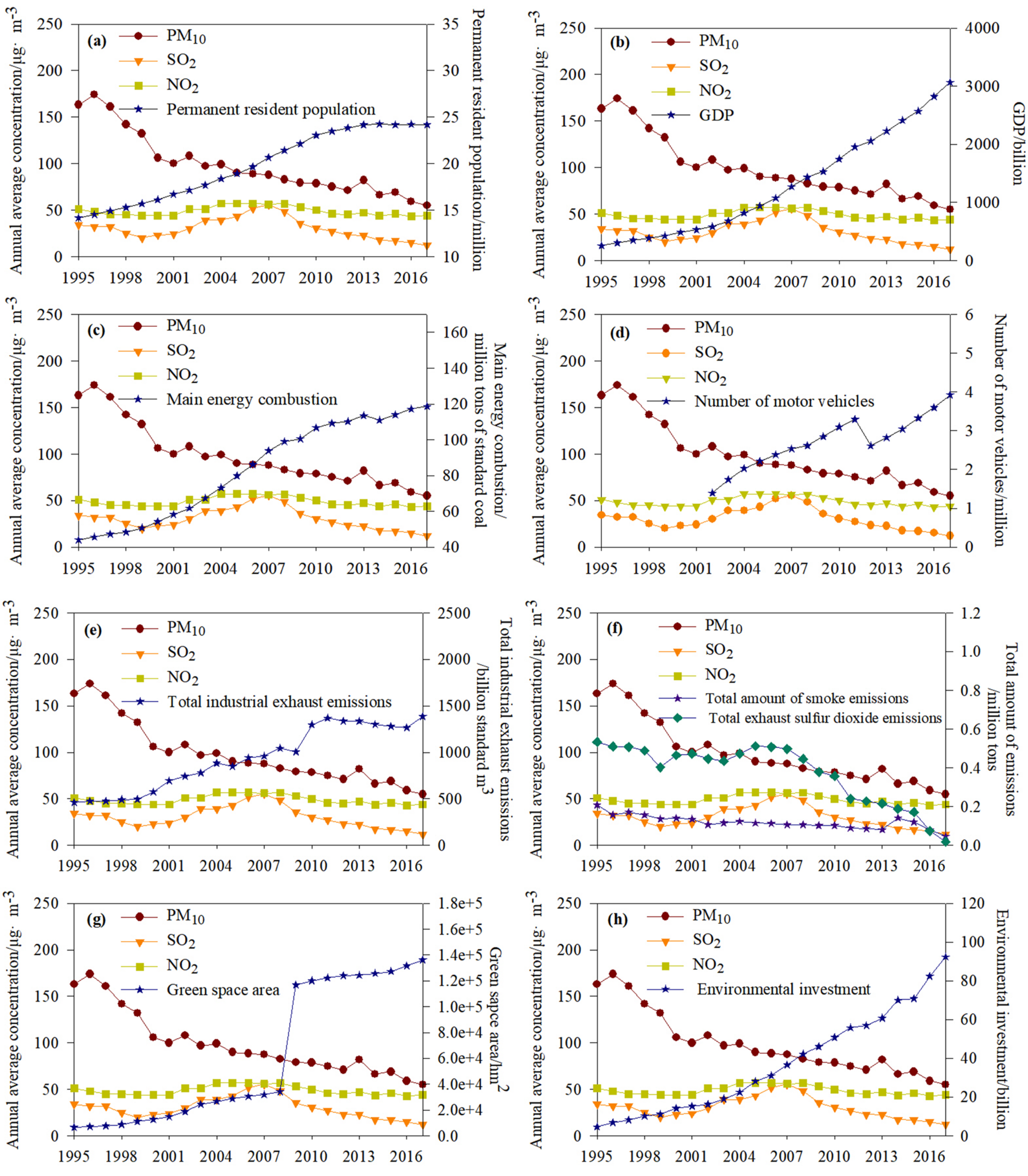

Figure 5. Annual change in average concentrations of three pollutants (PM_{10}, SO_2, NO_2) relative to (**a**) permanent resident population, (**b**) gross domestic product (GDP), (**c**) energy combustion, (**d**) number of motor vehicles, (**e**) total industrial exhaust emissions, (**f**) total amount of smoke emissions and exhaust sulfur dioxide emissions, (**g**) green space area, and (**h**) environmental investment in Shanghai during 1995–2017.

tons and 18.5 thousand tons, respectively, in 2017[34] (Fig. 5). However, energy consumption (EC) has increased, from 4,392.48 × 10^4 tons of standard coal in 1995 to 11,858.96 × 10^4 tons of standard coal in 2017, the number of motor vehicles (MV) has increased, from 1.39 million in 2002 to 3.92 million in 2017[34] (Fig. 5), and the volume of total industrial exhaust emissions (IEE) has increased, from 4,625 billion standard m^3 in 1995 to 13,867 billion standard m^3 in 2017[34] (Fig. 5). Although ambient air quality in Shanghai municipality has improved slightly in recent decades as a result of its environmental regulations (Fig. 5), Shanghai is still one of the cities with the highest levels of air pollutants worldwide[48].

	PM_{10}	SO_2	NO_2
GS	− 0.984**	− 0.410	− 0.153
IEE	− 0.940**	− 0.328	− 0.080
SE	0.842**	0.144	− 0.051
SDE	0.699**	0.707**	0.491*
PRP	− 0.979**	− 0.401	− 0.159
GDP	− 0.837**	− 0.428*	− 0.153
EC	− 0.901**	− 0.192	− 0.145
MV	− 0.942**	− 0.602*	− 0.705**
EI	− 0.849**	− 0.417*	− 0.153

Table 3. Correlations between pollutants and socio-economic indicators based on yearly data for the period 1995–2017. GS: green space area; IEE: total industrial exhaust emissions; SE: total amount of smoke emissions; SDE: total amount of exhaust sulfur dioxide emissions; PRP: permanent resident population; GDP: gross domestic product; EC: energy combustion; MV: number of motor vehicles; EI: environmental investment. $^{**}p < 0.01$; $^{*}p < 0.05$.

The correlations between GS, IEE, SE, SDE, PRP, GDP, EC, MV, EI, and air concentrations of PM_{10}, SO_2 and NO_2 are shown in Table 3. Although there have been large increases in PRP, GDP, EC, MV, and IEE in Shanghai in recent years, the increase in EI and the decrease in SE and SDE have compensated for the negative effects of the other factors, leading to positive effects in decreasing the concentrations of PM_{10}, SO_2, and NO_2. The results revealed that investments in environmental protection and pollution control strategies were the main factors affecting accumulation of PM_{10}, SO_2, and NO_2, indicating that such strategies are effective in reducing air pollution. The control in SE and SDE, and increase in EI and GS may be masking the increase in EC, MV, and IEE, leading to significant decrease in PM_{10}, and slight decrease in NO_2 and SO_2. The increased vehicle emissions and main energy would also help explain the relative stability NO_2 and SO_2 levels. As a pioneering city in the construction of ecological civilization, Shanghai has implemented several master plans to optimize GS in integration with an environmental sustainability agenda[49]. The implementation of ecological redline policy in Shanghai municipality could guarantee that GS be increased systematically or stabilized at this level[50] toward increasing the air quality. However, due to the lack in more detailed emission data per activity sector for all the pollutants, it is difficult to provide more concrete and quantitative evidence of the reasons that are driving the changes in the air quality, and explain if changes in air quality are really happening or if industrial sources are just getting better at not emitting the pollutants being monitored. Further studies are needed to reveal the percentage contribution of emission sources and atmospheric processes to the emissions of the pollutants.

Conclusions

This study analyzed temporal variations in the concentrations of air pollutants ($PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2, and CO), the major pollutant on polluted days, and the number of non-attainment days in Shanghai municipality from January 2015 to December 2018. Based on 4-year data from the Shanghai Environmental Monitoring Center, the overall status of air quality in Shanghai has improved. The number of days that met CAAQS Grade II standards increased from 258 in 2015 to 296 in 2018.

We found that SO_2 was rarely the "major pollutant", indicating effective control of coal combustion and implementation of desulphurization system in Shanghai municipality. However, $PM_{2.5}$ pollution in wintertime and O_3 pollution in summertime are still major challenges to air quality improvement in Shanghai municipality. Our findings suggest that the most frequent major pollutant in Shanghai municipality is O_3 (110 days in 2015, 84 days in 2016, 126 days in 2017, 113 days in 2018), followed by $PM_{2.5}$ (120 days in 2015, 104 days in 2016, 67 days in 2017, 61 days in 2018) and NO_2 (50 days in 2015, 67 days in 2016, 79 days in 2017, 63 days in 2018). O_3 is a complex secondary pollutant that is difficult to control effectively. The non-clear decrease in O_3_8h concentration from 2015 to 2018 and a peak in O_3_8h concentration in 2017 indicate a need for further studies on O_3 formation and control strategies.

Statistical analysis suggested that different air pollutants were significantly correlated with each other, apart from SO_2 and O_3. Significantly positive correlations between $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 were observed, suggesting that these pollutants may have originated from the same sources (e.g., vehicle and coal combustion emissions) or were impacted by the same drivers. The correlation results suggested that temperature (T) significantly impacted accumulation of all six pollutants in Shanghai municipality, while precipitation (*Prec*) and relative air humidity (*RH*) affected accumulation of some pollutants. Lower accumulation of PM, SO_2, NO_2, CO and more serious O_3 pollution in Shanghai were revealed in months with higher temperature and more precipitation. The correlation between the socio-economic factors and the air pollutants suggest that further rigorous measures are needed to control air pollution in the city. Investments in environmental protection and pollution control strategies were the main factors reducing accumulation of PM_{10}, SO_2, and NO_2, indicating that these strategies are effective in reducing air pollution. Overall, this study provided scientific insights into impacts of meteorological factors and socio-economic indicators on air pollution in Shanghai.

	Pollutant concentration limit (μg m^{-3})									
	SO_2		NO_2		PM_{10}	CO (mg m^{-3})		O_3		$PM_{2.5}$
IAQI	**24-h average**	**1-h average[a]**	**24-h average**	**1-h average[a]**	**24-h average**	**24-h average**	**1-h average[a]**	**1-h average**	**8-h average**	**24-h average**
0	0	0	0	0	0	0	0	0	0	0
50	50	150	40	100	50	2	5	160	100	35
100	150	500	80	200	150	4	10	200	160	75
150	475	650	180	700	250	14	35	300	215	115
200	800	800	280	1200	350	24	60	400	265	150
300	1600	[b]	565	2340	420	36	90	800	800	250
400	2100	[b]	750	3090	500	48	120	1000	[c]	350
500	2620	[b]	940	3840	600	60	150	1200	[c]	500

Table 4. Individual air quality index (IAQI) and corresponding pollutant concentration limit[52]. [a]1-h average concentration limits of SO_2, NO_2, and CO are only used in real-time reporting, and the 24-h average concentration limits of SO_2, NO_2, and CO are used in daily reporting. [b]When 1-h average concentration limit of SO_2 is higher than 800 μg m^{-3}, the individual air quality index of SO_2 is not reported and the reported individual air quality index of SO_2 is calculated by 24-h average concentration limits. [c]When 8-h average concentration limit of O_3 is higher than 800 μg m^{-3}, the individual air quality index of 8-h average concentration of SO_2 is not reported and the reported individual air quality index of SO_2 is calculated by 1-h average concentration limit.

Methods

The most recent CAAQS were published in 2012[8,51], when $PM_{2.5}$ and O_3_8h were added for the first time[24]. These latest CAAQS set annual, 24-h average, and 1-h average concentration limits for SO_2 and NO_2, annual and 24-h average concentration limits for $PM_{2.5}$ and PM_{10}, 24-h average and 1-h average concentration limits for CO, and maximum 8-h average and 1-h average concentration limits for O_3. In the same year, a 'Technical Regulation on Ambient Air Quality Index (on trial)' (HJ 633–2012) released by the Chinese Ministry of Environmental Protection (MEP)[52] replaced air pollution index (API) with AQI and divided air quality into six classes: 0–50 (Level I, excellent), 51–100 (Level II, good), 101–150 (Level III, lightly polluted), 151–200 (Level IV, moderately polluted), 201–00 (Level V, heavily polluted), and above 300 (Level VI, severely polluted)[8,28]. Daily individual AQI (IAQI) is calculated from the concentrations of individual pollutants, and the AQI value is determined to be the maximum IAQI of the six pollutants. When daily AQI is greater than 50, the pollutant that has the highest IAQI index is referred to as the daily 'major pollutant' contributing most to the air quality deterioration[8,24, 28]. When daily IAQI is greater than 100, air quality does not meet the CAAQS-Grade II level for 24-h average $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, or maximum 8-h average O_3, and such days are considered 'non-attainment days'[24]. The corresponding concentration limits of $PM_{2.5}$, PM_{10}, SO_2, NO_2, 24-h average CO, and O_3_8h when IAQI equals 50 or 100 are shown in Table 4.

$$AQI = \max\left\{IAQI_1, IAQI_2, IAQI_3, \ldots, IAQI_p\right\}$$

where *IAQI is* individual air quality index and *p* is pollutant; and

$$IAQI_p = \frac{IAQI_{Hi} - IAQI_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + IAQI_{Lo}$$

where $IAQI_p$ is individual air quality index of pollutant *p*, C_p is concentration of pollutant *p*, BP_{Hi} is high-value pollutant concentration limit when close to C_p (in Table 4), BP_{LO} is low-value pollutant concentration limit when close to C_p (in Table 4), $IAQI_{Hi}$ is the individual air quality index corresponding to BP_{Hi}, and $IAQI_{LO}$ is the individual air quality index corresponding to BP_{LO}.

Data on the real-time daily average concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2 and the maximum 8-h average concentration of O_3 at nine national air quality monitoring stations (Fig. 6) were obtained from the Shanghai Environmental Monitoring Center. Data on different air quality levels were obtained from Shanghai Environmental Bulletin (2015–2017) and Shanghai Ecological Environmental Bulletin (2018), which is open-access (https://sthj.sh.gov.cn/hb/fa/cms/shhj/list_login.jsp?channelId=2144). Monthly meteorological data (*Prec*, *W*, *T*, and *RH*) from two ground-level monitoring sites were downloaded from the China Meteorological Data Sharing Service System (https://data.cma.cn/).

CO is measured using the non-dispersive infrared absorption method[8,51], $PM_{2.5}$ and PM_{10} are measured using the micro-oscillating balance method and the β absorption method[8,51], and SO_2, NO_2, and O_3 are measured by the fluorescence method, the chemiluminescence method, and the UV-spectrophotometry method, respectively[8,51]. Correlation analysis (using SPSS 16.0) was applied to determine the relevance of the six pollutants, meteorological factors, and socio-economic indicators. Independence and normality tests were performed before the correlation analysis. Pearson correlation analysis was performed when the data were normally distributed, otherwise Spearman correlation analysis was applied.

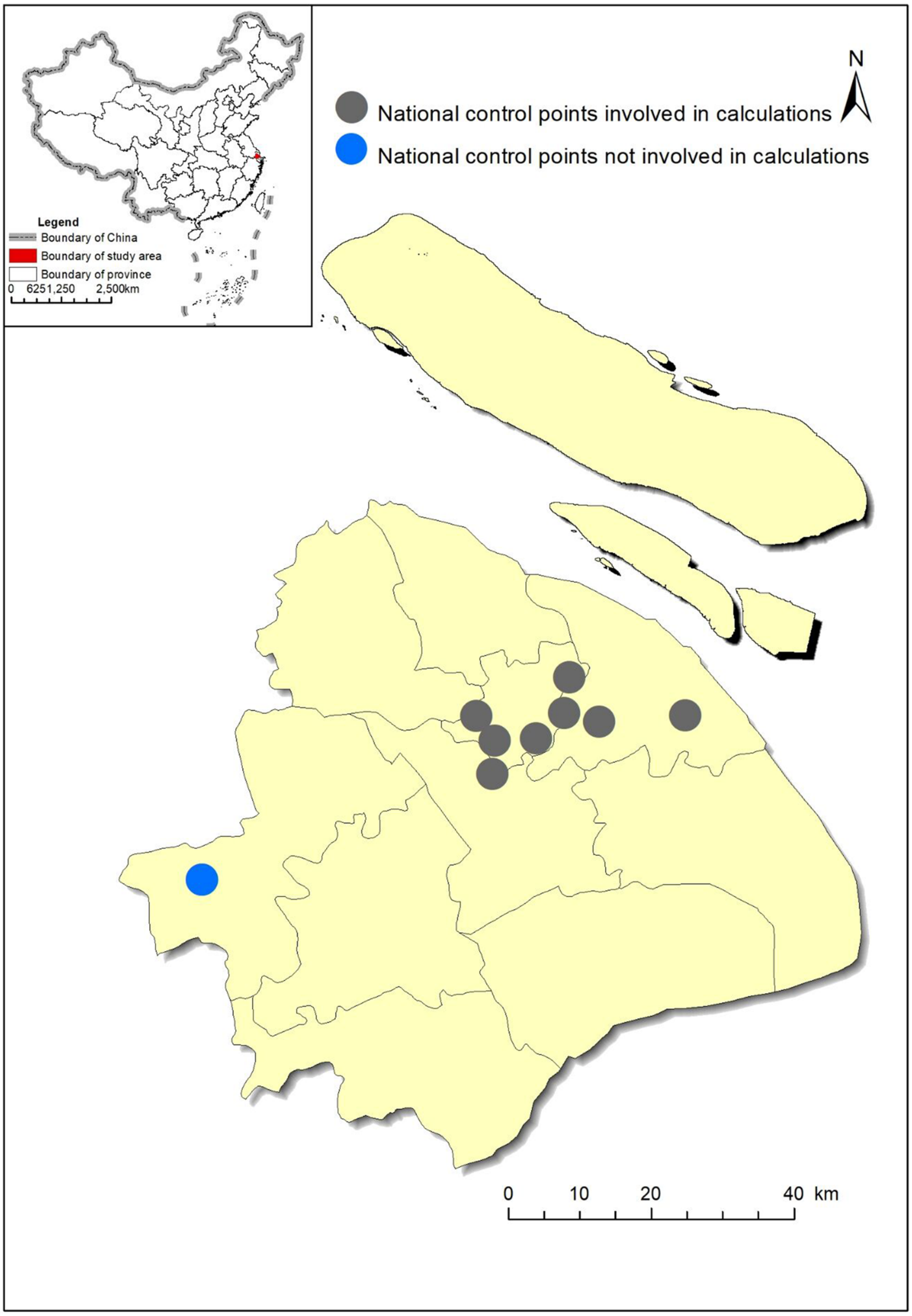

Figure 6. Location of national air quality monitoring stations in Shanghai municipality.

Data availability

All relevant data are available upon request from the authors.

Received: 8 January 2020; Accepted: 19 June 2020

References

1. He, K., Huo, H. & Zhang, Q. Urban air pollution in China: Current status, characteristics, and progress. *Annu. Rev. Energy Environ.* **27**, 397–431 (2002).
2. Chan, C. K. & Yao, X. Air pollution in mega cities in China. *Atmos. Environ.* **42**, 1–42 (2008).
3. Kan, H., Chen, R. & Tong, S. Ambient air pollution, climate change, and population health in China. *Environ. Int.* **42**, 10–19 (2012).
4. Zhao, S. P. *et al.* Annual and diurnal variations of gaseous and particulate pollutants in 31 provincial capital cities based on in situ air quality monitoring data from China National Environmental Monitoring Center. *Environ. Int.* **86**, 92–106 (2016).

5. Ouyang, Z. *et al.* Improvements in ecosystem services from investments in natural capital. *Science* **352**, 1455–1459 (2016).
6. Bai, R. Q., Lam, J. C. K. & Li, V. O. K. A review on health cost accounting of air pollution in China. *Environ. Int.* **120**, 279–294 (2018).
7. Xu, P., Chen, Y. & Ye, X. Haze, air pollution, and health in China. *Lancet* **382**, 2067 (2013).
8. He, J. *et al.* Air pollution characteristics and their relation to meteorological conditions during 2014–2015 in major Chinese cities. *Environ. Pollut.* **223**, 484–496 (2017).
9. Huang, R. *et al.* High secondary aerosol contribution to particulate pollution during haze events in China. *Nature* **514**, 218–222 (2014).
10. Zhao, J. *et al.* Quantification the impacts of socio-economic factors on air quality in Chinese cities from 2000 to 2009. *Environ. Pollut.* **167**, 148–154 (2012).
11. Guo, S. *et al.* Elucidating severe urban haze formation in China. *Proc. Natl. Acad. Sci. USA* **111**, 17373–17378 (2014).
12. Wang, L. *et al.* The 2013 severe haze over southern Heibei, China: Model evaluation, source apportionment, and policy implications. *Atmos. Chem. Phys.* **14**, 3151–3173 (2014).
13. Liu, Q., Baumgartner, J., Zhang, Y. & Schauer, J. Source apportionment of Beijing air pollution during a severe winter haze event and associated pro-inflammatory responses in lung epithelial cells. *Atmos. Environ.* **126**, 28–35 (2016).
14. Yang, J. & Zhang, B. Air pollution and healthcare expenditure: Implications for the benefit of air pollution control in China. *Environ. Int.* **120**, 443–455 (2018).
15. Zhang, J. J. & Mu, Q. Air pollution and defensive expenditures: Evidence from particulate-filtering facemasks. *J. Environ. Econ. Manag.* **92**, 517–536 (2018).
16. Li, R. *et al.* Air pollution characteristics in China during 2015–2016: Spatiotemporal variations and key meteorological factors. *Sci. Total Environ.* **648**, 902–915 (2019).
17. He, T. *et al.* Ambient air pollution and years of life lost in Ningbo, China. *Sci. Rep.* **6**, 22485. https://doi.org/10.1038/srep22485 (2016).
18. Ebenstein, A., Fan, M., Greenstone, M., He, G. & Zhou, M. New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. *Proc. Natl. Acad. Sci.* **114**, 10384–10389 (2017).
19. Yin, P. *et al.* Particulate air pollution and mortality in 38 of China's largest cities: Time series analysis. *BMJ* **356**, j667. https://doi.org/10.1136/bmj.j667 (2017).
20. Song, C. *et al.* Health burden attributable to ambient $PM_{2.5}$ in China. *Environ. Pollut.* **223**, 575–586 (2017).
21. Li, J. *et al.* Estimation of $PM_{2.5}$ mortality burden in China with new exposure estimation and local concentration-response function. *Environ. Pollut.* **243**, 1710–1718 (2018).
22. Zou, B. *et al.* Air pollution intervention and life-saving effect in China. *Environ. Int.* **125**, 529–541 (2019).
23. Feng, L. & Liao, W. J. Legislation, plans, and policies for prevention and control of air pollution in China: Achievements, challenges, and improvements. *J. Clean. Prod.* **112**, 1549–1558 (2016).
24. Song, C. *et al.* Air pollution in China: Status and spatiotemporal variations. *Environ. Pollut.* **227**, 334–347 (2017).
25. Florig, H. K., Sun, G. & Song, G. E. Evolution of particulate regulation in China-prospects and challenges of exposure-based control. *Chemosphere* **49**, 1163–1174 (2002).
26. Xue, T. *et al.* Spatiotemporal continuous estimates of $PM_{2.5}$ concentrations in China, 2000–2016: A machine learning method with inputs from satellites, chemical transport model, and ground observations. *Environ. Int.* **123**, 345–357 (2019).
27. Xia, Y. *et al.* Assessment of socioeconomic costs to China's air pollution. *Atmos. Environ.* **139**, 14–156 (2016).
28. Chen, S., Guo, C. & Huang, X. Air pollution, student health, and school absences: Evidence from China. *J. Environ. Econ. Manag.* **92**, 465–497 (2018).
29. Maji, K. J., Ye, W., Arora, M. & Nagendra, S. M. S. $PM_{2.5}$-related health and economic loss assessment for 338 Chinese cities. *Environ. Int.* **121**, 392–403 (2018).
30. Jourry, T. Y. Cleaner air for China. *Nat. Geosci.* **12**, 497 (2019).
31. van der A, R. J. *et al.* Cleaning up the air: Effectiveness of air quality policy for SO_2 and NO_2 emissions in China. *Atmos. Chem. Phys.* **17**, 1775–1789 (2017).
32. Jing, B. Y. *et al.* Development of a vehicle emission inventory with high temporal-spatial resolution based on NRT traffic data and its impact on air pollution in Beijing- Part 1: Development and evaluation of vehicle emission inventory. *Atmos. Chem. Phys.* **16**, 3161–3170 (2016).
33. He, J. *et al.* Development of a vehicle emission inventory with high temporal-spatial resolution based on NRT traffic data and its impact on air pollution in Beijing- Part 2: Impact of vehicle emission on urban air quality. *Atmos. Chem. Phys.* **16**, 3171–3184 (2016).
34. Shanghai Municipal Statistical Bureau, Survey Office of the National Bureau of Statistics in Shanghai. Shanghai Statistical Yearbook. China Statistical Press, Beijing (2004–2018) (in Chinese).
35. Pusede, S. E. *et al.* On the temperature dependence of organic reactivity, nitrogen oxides, ozone production, and the impact of emission controls in San Joaquin Valley, California. *Atmos. Chem. Phys.* **14**, 3373–3395 (2014).
36. Fu, T. M., Zheng, Y., Paulot, F., Mao, J. & Yantosca, M. R. Positive but variable sensitivity of August surface ozone to large-scale warming in the southeast United States. *Nat. Clim. Change* **5**, 454–458 (2015).
37. Cheng, Z. *et al.* Status and characteristics of ambient $PM_{2.5}$ pollution in global megacities. *Environ. Int.* **89–90**, 212–221 (2016).
38. Wang, Y., Ying, Q., Hu, J. & Zhang, H. Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013–2014. *Environ. Int.* **73**, 413–422 (2014).
39. Huang, Y. *et al.* Quantification of global primary emissions of $PM_{2.5}$, PM_{10}, and TSP from combustion and industrial process sources. *Environ. Sci. Technol.* **48**, 13834–13843 (2014).
40. He, J., Wu, L., Mao, H. & Li, R. Impacts of meteorological conditions on air quality in urban Langfang, Hebei Province. *Res. Environ. Sci.* **29**, 791–799 (2016).
41. Ran, L. *et al.* Ozone production in summer in the megacities of Tianjin and Shanghai, China: A comparative study. *Atmos. Chem. Phys.* **12**, 7531–7542 (2012).
42. Wang, T. *et al.* Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. *Sci. Total Environ.* **575**, 1582–1596 (2017).
43. Pusede, S., Steiner, A. & Cohen, R. Temperature and recent trends in the chemistry of continental surface ozone. *Chem. Rev.* **115**, 3898–3918 (2015).
44. Zhang, H., Hu, J. & Qi, Y. Emission characterization, environmental impact, and control measure of $PM_{2.5}$ emitted from agricultural crop residue burning in China. *J. Clean. Prod.* **149**, 629–635 (2017).
45. Zhang, X. *et al.* Dust deposition and ambient PM_{10} concentration in Northwest China: Spatial and temporal variability. *Atmos. Chem. Phys.* **17**, 1699–1711 (2017).
46. Yang, X. *et al.* Distinct impact of different types of aerosols on surface solar radiation in China. *J. Geophys. Res. Atmos.* **11**, 6459–6471 (2016).
47. Yang, Y. *et al.* Seasonal variations and size distributions of water-soluble ions of atmospheric particulate matter at Shigatse, Tibetan plateau. *Chemosphere* **145**, 560–567 (2016).
48. Watts, J. China: The air pollution capital of the world. *Lancet* **366**, 1761–1762 (2005).

49. Chen, J. *et al.* Quantifying ecosystem services supply and demand shortfalls and mismatches for management optimization. *Sci. Total Environ.* **650**, 1426–1439 (2019).
50. Bai, Y. *et al.* Developing China's Ecological Redline Policy using ecosystem services assessments for land use planning. *Nat. Commun.* **9**, 3034 (2018).
51. MEP, the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. Ambient Air Quality Standards (GB 3095-2012) (2012).
52. MEP. Technical Regulation on Ambient Air Quality Index (On Trial) (HJ 633-2012) (2012).

Acknowledgements

This study was supported by the Key Research Program of Frontier Sciences (Grant No. ZDBS-LY-7011), National Key Research and Development Program of China (2017YFF0207303; 2016YFC0503004). The online sharing of air quality data by the Shanghai Environmental Monitoring Center is gratefully acknowledged.

Author contributions

Y.C. and B.J. designed the study, performed the data analysis, and wrote the manuscript. Y.B. and H.L. participated in data analysis. Y.B., H.L. and J.M.A. reviewed and approved the manuscript.

Competing interests

The authors declare no competing interests.

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