Environmental Research Letters

LETTER • OPEN ACCESS

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To cite this article: B Silver *et al* 2018 *Environ. Res. Lett.* **13** 114012

Environmental Research Letters

OPEN ACCESS

RECEIVED
10 July 2018

REVISED
18 September 2018

ACCEPTED FOR PUBLICATION
10 October 2018

PUBLISHED
13 November 2018

LETTER

Substantial changes in air pollution across China during 2015–2017

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Keywords: air pollution, China, ozone, particulate matter

Supplementary material for this article is available online

Abstract

China's rapid industrialisation and urbanisation has led to poor air quality. The Chinese government have responded by introducing policies to reduce emissions and setting ambitious targets for ambient $PM_{2.5}$, SO_2, NO_2 and O_3 concentrations. Previous satellite and modelling studies indicate that concentrations of these pollutants have begun to decline within the last decade. However, prior to 2012, air quality data from ground-based monitoring stations were difficult to obtain, limited to a few locations in major cities, and often unreliable. Since then, a comprehensive monitoring network, with over 1000 stations across China has been established by the Ministry of Ecology and Environment (MEE). We use a three-year (2015–2017) dataset consisting of hourly $PM_{2.5}$, O_3, NO_2 and SO_2 concentrations obtained from the MEE, combined with similar data from Taiwan and Hong Kong. We find that at 53% and 59% of stations, $PM_{2.5}$ and SO_2 concentrations have decreased significantly, with median rates across all stations of -3.4 and -1.9 $\mu g\,m^{-3}\,year^{-1}$ respectively. At 50% of stations, O_3 maximum daily 8 h mean (MDA8) concentrations have increased significantly, with median rates across all stations of 4.6 $\mu g\,m^{-3}\,year^{-1}$. It will be important to understand the relative contribution of changing anthropogenic emissions and meteorology to the changes in air pollution reported here.

Introduction

Rapid economic growth and large increase in emissions has led to serious air quality issues across China. Annual $PM_{2.5}$ (mass of particulate matter with a diameter less than 2.5 μm) exceeds 100 $\mu g\,m^{-3}$ in polluted regions of northeast China (Ma *et al* 2014, Zhang and Cao 2015). Exposure to ambient (outdoor) $PM_{2.5}$ is estimated to cause 0.87–1.36 million deaths each year across China (Apte *et al* 2015, Lelieveld *et al* 2015, Gu and Yim 2016, Cohen *et al* 2017). Health impacts from exposure to ambient $PM_{2.5}$ cause losses equal to 1.1% of gross domestic product at the national level (Xia *et al* 2016) with losses of 1.3% in the Pearl River Delta (PRD) and 1.0% in Shanghai (Kan and Chen 2004, Huang *et al* 2012).

To address issues of poor air quality, the Chinese government has introduced policies to reduce pollutant emissions and has established ambient concentration targets for provincial and municipal authorities (Jin *et al* 2016). Despite having developed a comprehensive environmental legal framework to control pollution during the 1980s and 1990s, most control methods were not widely enforced until the 2000s (Florig *et al* 2002, Beyer 2006, Feng and Liao 2016). Desulfurization of coal-fired power plants, introduction of electrostatic precipitators (Liu *et al* 2015), closure of polluting power plants and increased efficiency (Guan *et al* 2014), have resulted in decreases in emissions of sulphur dioxide (SO_2) and $PM_{2.5}$ (Lu *et al* 2010, Klimont *et al* 2013, Van Der A *et al* 2017). Shifts towards cleaner fuels and electricity for cooking and heating in rural areas has contributed to reduced residential $PM_{2.5}$ emissions (Tao *et al* 2018). Regulation of nitrogen oxides (NO_x) has resulted in installation of NO_x filtering systems on power plants, phasing out heavily polluting factories and new emission standards for vehicles (Liu *et al* 2017, Wu *et al* 2017). NO_x emissions over 48 Chinese cities increased by 52% from 2005 to 2011 before decreasing by 21% between 2011–2015 (Liu *et al* 2017). In response to the 2012–13 air pollution 'crisis,' where very poor air quality triggered a public outcry, the state council issued the 'Action Plan on Prevention and Control of Air Pollution' that prioritised $PM_{2.5}$ reduction in megacity regions (Sheehan *et al* 2014, Wang *et al* 2018). According to the estimates made in the Multi-resolution Emission Inventory for China, emissions of SO_2, NO_x, $PM_{2.5}$, PM_{10} (mass of particulate matter with a diameter less than 10 μm) and carbon monoxide (CO) have decreased during 2013–2017 (Zheng *et al* 2018).

Understanding the impacts of changing emissions on pollutant concentrations is necessary to assess past management policies and identify future policy challenges. Longer term records of surface air pollutants are available across the PRD, showing that $PM_{2.5}$ concentrations increased between 2000–2005 before decreasing from 2005–2010 (Wang *et al* 2016). Elsewhere across China a lack of widespread surface measurement data prior to 2012 means most previous analyses have relied on satellite data, visibility observations or emission estimates combined with modelling to establish air quality trends.

A number of studies have used satellite retrievals of aerosol optical depth to estimate trends in $PM_{2.5}$ concentrations. Peng *et al* (2016) reported increased $PM_{2.5}$ concentrations across China between 1999–2011. Ma *et al* (2016a) reported a positive trend in $PM_{2.5}$ across China between 2004 –2007, followed by a negative trend between 2007–2013. Lin *et al* (2018) found Chinese $PM_{2.5}$ concentrations increased between 2001–2005, before decreasing from 2006–2015. Fu *et al* (2014) used visibility data across the North China Plain (NCP) to show a positive trend in low visibility days between 1980–1995, little trend between 1995–2003 followed by a reduction in low visibility days between 2003–2010, particularly in winter. Visibility data has also been used to estimate that annual mean $PM_{2.5}$ in Beijing increased between 1973–2013 by an average of 0.6 $\mu g\ m^{-3}\ year^{-1}$ (Han *et al* 2016). A modelling study suggests that population-weighted $PM_{2.5}$ concentrations across China increased by 53% between 1960–2010 and by 10%–35% between 1990–2010 (Butt *et al* 2017). Li *et al* (2017a) use satellite and *in situ* observations to downscale a global model and estimate that in East Asia, annual population-weighted mean $PM_{2.5}$ increased significantly by 0.86 $\mu g\ m^{-3}\ year^{-1}$ during 1998–2013, with an insignificantly decreasing trend during 2006–2013.

Satellite observations show that SO_2 concentrations over the NCP region peaked in 2007, decreasing by 50% between 2005–2015 (Krotkov *et al* 2016). Declines in SO_2 across China are also more widespread, with a 50% decline in SO_2 concentrations reported across the most polluted provinces in China between 2005–2015 (Ling *et al* 2017, Van Der A *et al* 2017). Li *et al* (2017b) estimate that SO_2 loading over China decreased by a factor of five between 2007–2016, by which time 350 million fewer people were exposed to dangerous concentrations.

Satellite observations have shown that similarly to SO_2 and $PM_{2.5}$, nitrogen dioxide (NO_2) has begun to decrease across China (Zhang *et al* 2012, 2018, Irie *et al* 2016, Krotkov *et al* 2016). Across the NCP, NO_2 concentrations increased by 50% between 2005–2011, before returning to 2005 levels by 2015 (Krotkov *et al* 2016). The same trend with a maximum in 2011 was observed when averaging across the whole of China (Irie *et al* 2016). Gu *et al* (2013) found that while the trend in NO_x emissions was positive across the whole of China during 2005–2010, the more economically developed regions such as the PRD and municipalities of Beijing and Shanghai had comparatively lower concentrations or negative trends.

Satellite observations suggest ozone (O_3) concentrations have been steadily increasing across China at a rate of 7% per year between 2005–2010 (Verstraeten *et al* 2015). Although there are no long term records of surface O_3 measurements in urban areas of China, there is evidence of positive trends at background sites. During 2003–2015, maximum daily average 8 h mean (MDA8) O_3 concentrations increased at a rate of 1.13 ppb $year^{-1}$ at a monitoring station 100 km northeast of Beijing (Ma *et al* 2016b). An increase of 0.25 ppb $year^{-1}$ was recorded at a remote background site in western China between 1994–2013 (Xu *et al* 2016), and in southern China, and at a background site in Hong Kong an increase of 0.58 ppb $year^{-1}$ between 1994–2007 was recorded (Wang *et al* 2009).

Most of our understanding of recent trends in air pollution across China comes from satellite studies or from relatively few *in situ* observations. There have been very few attempts to use data from surface monitoring stations to assess recent trends. Here we use data from >1600 surface monitoring stations across China and Taiwan for the period 2015–2017 to explore recent trends in the concentrations of air pollutants.

Methods

Three year time series (January 2015–December 2017) of hourly concentrations of $PM_{2.5}$, PM_{10}, CO, O_3, SO_2 and NO_2 were downloaded for stations operated by the environmental protection departments for Mainland China (MC), Hong Kong (HK) and Taiwan (TW). Data for MC was downloaded from http://beijingair.sinaapp.com/ which had obtained the data from http://pm25.in, a mirror of data from the official Ministry of Ecology and Environment download platform (http://106.37.208.233:20035/). Similar data has been used in other studies (e.g. (Rohde and Muller 2015, Liang *et al* 2016, Leung *et al* 2018)). HK data was

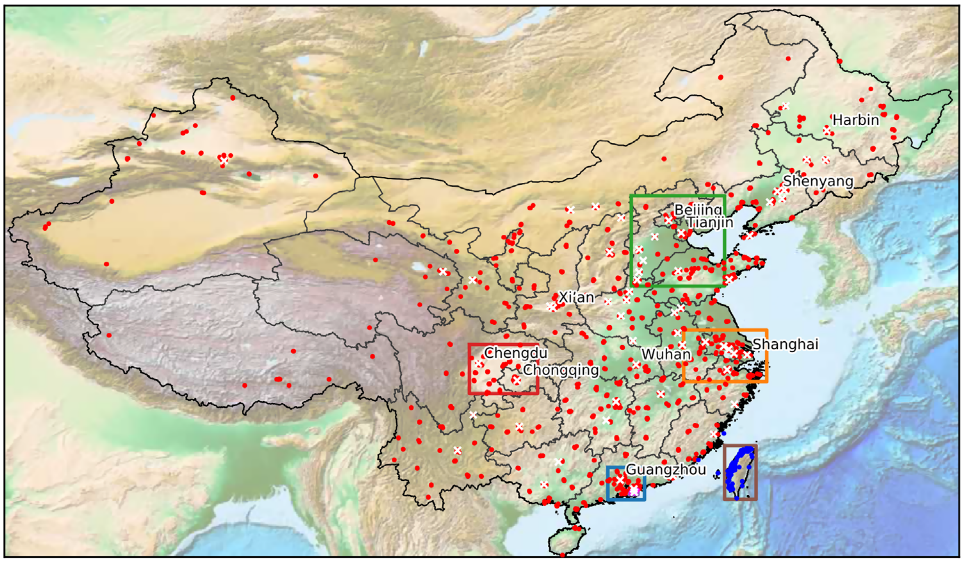

Figure 1. Location of air quality stations in Mainland China (red), Taiwan (blue) and Hong Kong (magenta) used in this analysis. The 60 largest cities by population are marked with white crosses, of which the 10 largest are labelled.

Table 1. The number of monitoring stations available for each pollutant and the number of stations that were removed during data checking.

	Pollutant			
Type	NO_2	$PM_{2.5}$	O_3	SO_2
Initial number of stations	1689	1689	1687	1689
Number of stations with >5% consecutive repeats	148	100	1	N/A
Number of stations removed due to <90% of data being present	520	505	339	296
Number of stations removed due to 'day-to-day' repeats	10	37	11	25
Number of stations remaining in the analysis	1159	1147	1337	1368

downloaded from the HK Environmental Protection department (https://cd.epic.epd.gov.hk/EPICDI/air/station/) and TW data was downloaded from the TW Environmental Protection Agency (https://taqm.epa.gov.tw/taqm/en/YearlyDataDownload.aspx). MC data has been described in detail by Zhang and Cao (2015). TW data (excluding aerosol measurements) was reported as a mole fraction, so these were converted into mass concentration to match MC and HK data by using meteorological data (73 stations), and assuming standard pressure and a temperature of 25 °C where this was unavailable (4 stations). Together these sources provided data from 1689 monitoring stations, with 13 from HK (the roadside stations are not used), 75 from TW and 1601 from MC. Locations of the stations are shown in figure 1.

Previously there have been doubts about the reliability of air quality monitoring data from China, due to manipulation of data by local environmental protection bureaus which resulted in discontinuities around air quality targets (Andrews 2008, Ghanem and Zhang 2014). However, by comparing Chinese data with data from United States Embassy and Consulate monitoring stations, it has been shown that data is more reliable since 2013 (Liang *et al* 2016, Stoerk 2016). Other quality issues with the MC data have been previously noted including a high proportion of repeating values at some sites (Rohde and Muller 2015), and periods when reported $PM_{2.5}$ concentrations exceed PM_{10} concentrations (Liu *et al* 2016b).

To address potential quality issues we applied the following procedure to all the data used in the study. First, we removed consecutive repeats from the data. Values were removed from NO_2 and $PM_{2.5}$ time series when there were >4 consecutive repeats, and for O_3 where there were >24 consecutive repeats. 148 and 100 stations contained >5% consecutive repeats for NO_2 and $PM_{2.5}$ respectively and 1 station contained >5% repeats for O_3. The data contain a small fraction (<0.04%) of zero values, which are unlikely to be accurate and could be caused by lower precision around the detection limit. We remove zero values from the time series. After consecutive repeats and zeroes have been removed, if <90% of hourly data is available for the whole time series, it is removed. Finally, to remove day-to-day repeats, data were flagged if the daily mean had a low coefficient of variation in a certain period (see supplementary figure 1 examples, available online at stacks.iop.org/ERL/13/114012/mmedia). If >60 d were flagged, the station is removed. The number of stations identified at each stage of data quality checking are shown in table 1. The thresholds used were chosen by applying the procedure with a range of thresholds, and manually examining the datasets to verify whether suspect data were removed. The thresholds applied for the different pollutants are given in supplementary table 1. We test the sensitivity of our analysis to these thresholds and find the magnitude of the trends we calculate are not sensitive to the values of the thresholds we choose (supplementary table 2).

The hourly data is used to calculate monthly averages. We then deseasonalised the data (the results using non-deseasonalised data are shown in supplementary figure 2). To analyse the three-year time series for monotonic, linear trends, the Mann-Kendall test was used to assess the significance of trends (using a threshold of $p < 0.05$), and the Theil–Sen estimator was used to calculate the magnitude of the trend. Both tests are resistant to outliers, and do not require any assumptions about the data used (Carslaw 2015, Fleming *et al* 2018). Absolute trends were converted to relative trends by dividing by the 2015 to 2017 mean. For O_3, the trend tests were also applied to the MDA8 metric, which is used in the World Health Organisation's (WHO) air quality guidelines (AQGs). The R package '*openair*,' which contains a set of tools developed specifically for analysing air quality data, was used to perform this stage of the analysis (Carslaw and Ropkins 2012).

We specifically analyse trends for large urban clusters: Pearl River Delta (PRD), Yangtze River Delta (YRD), North China Plain (NCP), and Sichuan Basin (SCB). Additionally, we analyse trends for the Hong Kong Special Administrative Region (HK) (which is within the PRD domain) and Taiwan (TW).

Air pollutant concentrations and trends

Annual mean concentrations of air pollutants during 2015–2017 are shown in figure 2 and supplementary figures 3 and 4. Highest annual mean $PM_{2.5}$ concentrations are found in the provinces of Hebei, Henan and Shandong, which all have a median concentration of $>60\ \mu g\ m^{-3}$. Stations in Shanghai and Guangdong have lower $PM_{2.5}$ concentrations, while the lowest $PM_{2.5}$ concentrations ($20–25\ \mu g\ m^{-3}$) are found in Hong Kong, Taiwan and Xizang. The highest concentrations of SO_2 are found in Shanxi, which has a median concentration of $>60\ \mu g\ m^{-3}$, and in Hebei which has a median concentration of $37\ \mu g\ m^{-3}$. High NO_2 concentrations are found across the Tianjin, Hebei and Beijing region, as well as Shanghai, Hong Kong and Chongqing. The provinces with the highest median O_3 concentrations are the high elevation provinces of Xizang and Qinghai. Hong Kong and Chongqing have some of the lowest O_3 concentrations.

Figure 2 also shows trends in air pollutants during 2015–2017. The median trend in annual mean $PM_{2.5}$ concentration across all stations is $-3.4\ \mu g\ m^{-3}\ year^{-1}$ or $-7.2\%\ year^{-1}$. This is comparable to Zheng *et al* (2017), who find that the annual mean $PM_{2.5}$ across 74 Chinese cities decreased by 23.6% between 2013–2015 ($-7.9\%\ year^{-1}$). Lin *et al* (2018) used satellite data to suggest the Chinese $PM_{2.5}$ trend steepened from $-0.65\ \mu g\ m^{-3}\ year^{-1}$ between 2006–2010 to $-2.3\ \mu g\ m^{-3}\ year^{-1}$ between 2011–2015. Our work suggests that the rate of $PM_{2.5}$ decline has been sustained, or possibly even become faster, between 2015–2017. We find 58.4% of stations have significant $PM_{2.5}$ concentration trends, and of these, 90% are negative. PM_{10} concentrations exhibit similar trends (supplementary figure 5). The fraction of stations meeting the WHO's first Interim Target for annual average $PM_{2.5}$ concentration of $35\ \mu g\ m^{-3}$ rose from 15% in 2015 to 20% in 2017.

Figure 3 shows the relative trends in air pollutants at the province level (supplementary figure 6 shows absolute trends). Negative trends in $PM_{2.5}$ concentrations are widespread, with all provinces experiencing negative median trends except Shanxi and Jiangxi. Most provinces had trends of around $-10\%\ year^{-1}$, with faster reductions in some areas including Beijing municipality ($-14.4\%\ year^{-1}$). Widespread reductions in $PM_{2.5}$ concentrations are consistent with trends estimated from satellite data for the period 2011–2015 (Lin *et al* 2018).

The median trend in annual mean SO_2 concentration across all stations is $-1.9\ \mu g\ m^{-3}\ year^{-1}$ or $-10.3\%\ year^{-1}$. 66% of stations have significant trends, and of these, 90% are negative. The mean exceedance rate of the WHO 24 h AQG fell from 10.8% in 2015 to 7.6% in 2017. Similarly to $PM_{2.5}$, negative trends in SO_2 concentrations are widespread across provinces (figure 3), with all having median negative trends apart from Hainan and Fujian, both of which have low absolute concentrations (supplementary figure 3).

There is no median trend in annual mean NO_2 concentration ($0.0\ \mu g\ m^{-3}\ year^{-1}$ or $0.1\%\ year^{-1}$). 48% of stations have significant trends, and of these, 54% are positive. The percentage of the stations that comply with the WHO's annual mean AQG of $40\ \mu g\ m^{-3}$ has declined, from 71% in 2015 to 66% in 2017. There is more heterogeneity in the spatial distribution of trends, with median positive trends in the SCB, YRD and PRD domains, but median negative trends in HK, NCP and TW (figure 2). The greater spatial heterogeneity of NO_2 trends could be partly due to its comparatively shorter lifetime, so that neighbouring regions can have opposing trends (e.g. HK and the PRD). The NO_2 concentration trends we report for 2015–2017 are more variable that the consistent declines in NO_x emissions (Liu *et al* 2016a, Van Der A *et al* 2017) and NO_2 concentrations (Krotkov *et al* 2016) reported for the period 2011–2015.

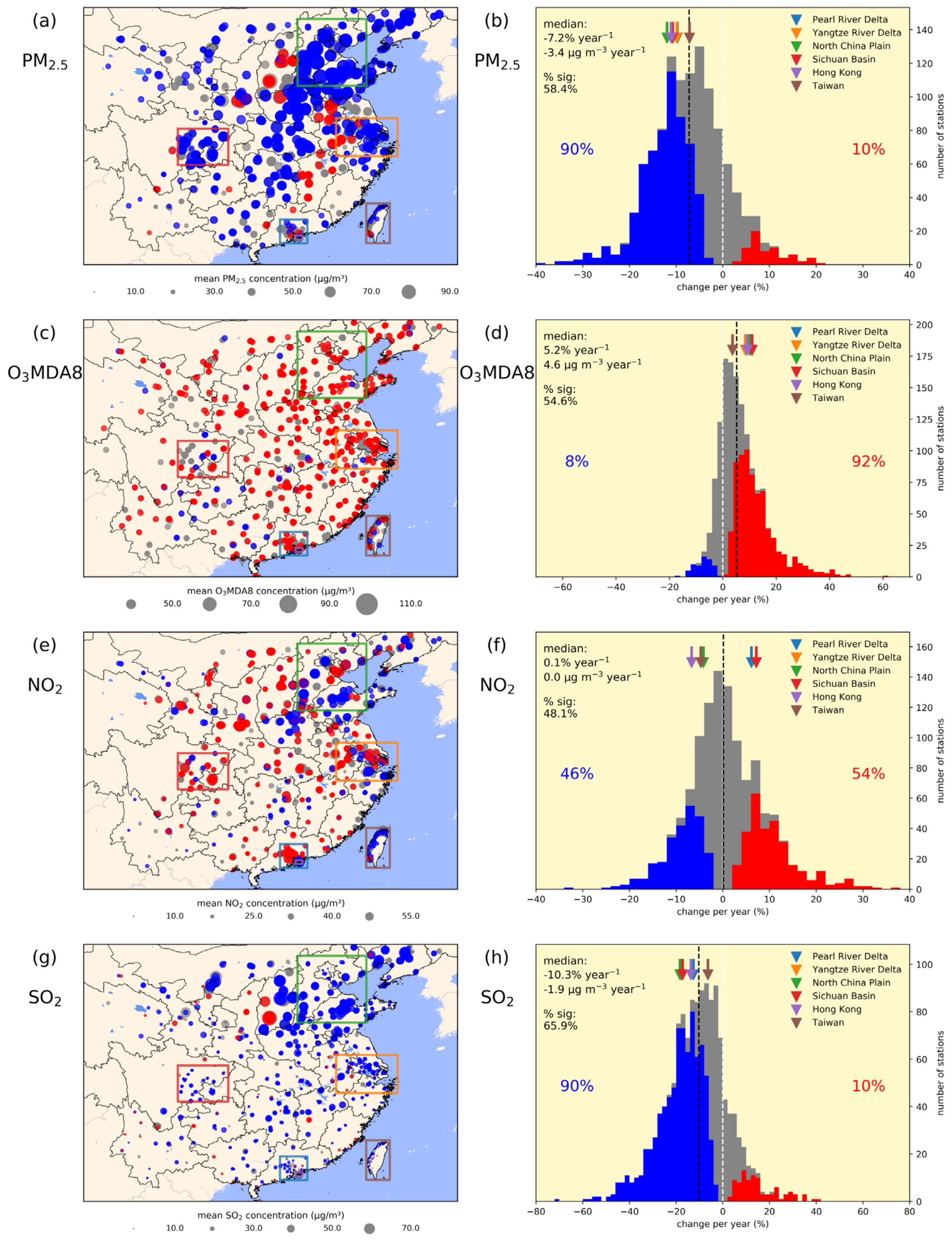

Figure 2. Trends in concentrations of (a), (b) $PM_{2.5}$, (c), (d) O_3 MDA8, (e), (f) NO_2, (g), (h) SO_2 across Mainland China, Hong Kong and Taiwan during 2015–2017. Left-hand panels (a), (c), (e), (g) show the sign of trend (blue: significant negative, red: significant positive, grey: insignificant) and mean concentration (size of circle). Right hand panels (b), (d), (f), (h) show the frequency of stations against the relative trends. The median relative and absolute trend as well as the percentage of stations with significant trends is shown on each panel. The percentage of significant trends that are negative (blue) or positive (red) are also shown. The black dotted line shows the median trend across all sites. Triangles show the median trend for the regional domains shown in the left-hand panels: Pearl River Delta (PRD), Yangtze River Delta (YRD), North China Plain (NCP), Sichuan Basin (SCB), Hong Kong Special Administrative Region (HK) and Taiwan (TW). The left panels are zoomed to show the trends over the more populous regions of China, while median trends and % of significant sites on the right panels refer to all Mainland China, Hong Kong and Taiwan.

In contrast to $PM_{2.5}$ and SO_2, annual mean O_3 MDA8 has a positive median trend of 4.6 $\mu g\ m^{-3}$ $year^{-1}$ or 5.2% $year^{-1}$. 55% of stations have significant trends, and of these, 92% are positive. Averaging across all stations, the percentage of days where the WHO AQG (100 $\mu g\ m^{-3}$) was exceeded for MDA8 rose from 9.8% in 2015 to 12.4% in 2017. Annual mean O_3 concentrations show similar relative and absolute trends (supplementary figures 7 and 8). The Tropospheric Ozone Assessment Report, which did

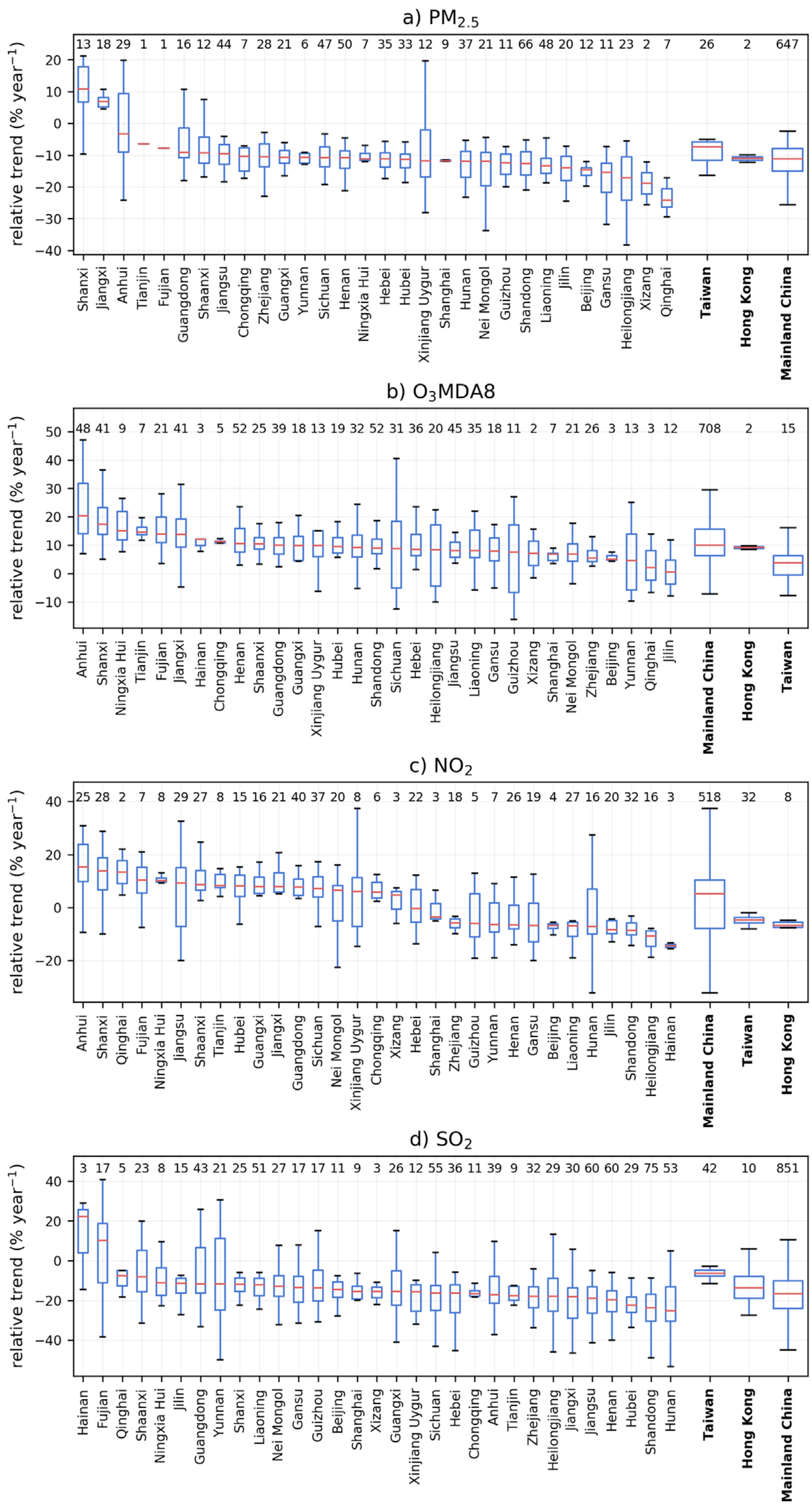

Figure 3. Relative trends in (a) $PM_{2.5}$, (b) O_3 MDA8, (c) NO_2 and (d) SO_2 by province or region (bolded). The median (red line), interquartile range (IQR) (box) and IQR $\pm$ IQR*1.5 (whiskers) of the trend across the stations in each province/region is shown. The number of stations in each province/region is indicated at the top of the plot.

not aggregate trends specifically for China due to lack of stations with long records, also reports significant positive trends over East Asia, (Chang *et al* 2017, Fleming *et al* 2018). All the megacity regions highlighted in figure 2 have medians greater than the overall median, and there are only 4 regions in figure 3 with median negative trends. During 2005–2013, Chinese megacity clusters shifted from a VOC-limited (NO_x saturated) O_3 production regime towards a mixed regime, due to reductions in NO_x emissions, which has lessened the NO_x titration effect resulting in increases in O_3 concentration (Jin and Holloway 2015). Meanwhile, increasing NO_x emissions in less developed cities has led to a shift from NO_x limited regimes towards mixed regimes, which have high O_3 production efficiency (Jin and Holloway 2015).

Discussion and conclusion

We find substantial changes in the concentrations of air pollutants across China during the period of 2015–2017. We report negative trends in annual mean $PM_{2.5}$ ($-3.4\ \mu g\ m^{-3}\ year^{-1}$) and SO_2 ($-1.9\ \mu g\ m^{-3}\ year^{-1}$) concentrations and positive trends in annual mean O_3 MDA8 ($4.7\ \mu g\ m^{-3}\ year^{-1}$) concentrations. The observed trends are widespread across China and occur consistently across most of the country. In contrast we find spatially variable changes in NO_2, with no overall trend across China. Trends in $PM_{2.5}$ and SO_2 concentrations are consistent with previous studies, that report negative trends in both $PM_{2.5}$ (Ma *et al* 2016a, Lin *et al* 2018) and SO_2 (Krotkov *et al* 2016, Van Der A *et al* 2017) between ~2007 and 2015. Our study therefore suggests that declines in $PM_{2.5}$ and SO_2 concentrations that have been reported for 2007–2015 continued between 2015 and 2017.

The trends we report are calculated over a relatively short period and could be caused by a variety of different factors. Air pollution is strongly dependent on weather. Interannual variability in meteorology and synoptic weather conditions (Leung *et al* 2018) may therefore play a role in the trends we observe here. Air pollution over China is influenced by variability in atmospheric circulation such as El Nino Southern Oscillation (ENSO) (Cao *et al* 2015, Zhao *et al* 2017) and the Asian monsoon (Li *et al* 2016, Cai *et al* 2017). El Nino years are associated with greater surface $PM_{2.5}$ in southern China and lesser $PM_{2.5}$ in northern China compared to La Nina years (Zhao *et al* 2017). ENSO variability is therefore unlikely to cause the spatially extensive trends in air pollutants across all of China that we report. It is possible that ENSO may have retarded the reduction in surface $PM_{2.5}$ over northern China during 2015–2017. Changes in land cover and local meteorological conditions also alter the emissions of natural aerosol and trace gases (Fu *et al* 2016), including dust and biogenic volatile organic compounds that can form secondary organic aerosol and alter concentrations of O_3. Leung *et al* (2018) suggest that $PM_{2.5}$ across the NCP will decrease by $0.5\ \mu g\ m^{-3}$ by the 2050s due to climate change, substantially less than the changes we report over the past 3 years. Since the trends over the period 2015–2017 are consistent with trends over the period 2007–2015, occur consistently across the country and coincide with declining Chinese anthropogenic emissions (Zheng *et al* 2018), we suggest that the trends are likely dominated by these emission changes. Future work needs to use air quality models to fully assess the contribution of different drivers of the trends reported here. It will be particularly important to establish what is causing the widespread increase in O_3 concentrations, so that emissions control policies can be most effectively targeted.

Acknowledgments

We acknowledge AIA Group and Natural Environment Research Council (NE/N006895/1) for funding.

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References

Andrews S Q 2008 Inconsistencies in air quality metrics: 'Blue Sky' days and PM_{10} concentrations in Beijing *Environ. Res. Lett.* **3** 034009

Apte J S, Marshall J D, Cohen A J and Brauer M 2015 Addressing global mortality from ambient $PM_{2.5}$ *Environ. Sci. Technol.* **49** 8057–66

Beyer S 2006 Environmental law and policy in the People's Republic of China *Chin. J. Int. Law* **5** 185–211

Butt E W, Turnock S T, Rigby R, Reddington C L, Yoshioka M, Johnson J S, Regayre L A, Pringle K J, Mann G W and Spracklen D V 2017 Global and regional trends in particulate air pollution and attributable health burden over the past 50 years *Environ. Res. Lett.* **12** 104017

Cai W, Li K, Liao H, Wang H and Wu L 2017 Weather conditions conducive to Beijing severe haze more frequent under climate change *Nat. Clim. Change* **7** 257–62

Cao Z, Sheng L, Liu Q, Yao X and Wang W 2015 Interannual increase of regional haze-fog in North China plain in summer by intensified easterly winds and orographic forcing *Atmos. Environ.* **122** 154–62

Carslaw D 2015 The openair manual open-source tools for analysing air pollution data *Manual for version 1.1–4* King's College London p 287 (http://openair-project.org/PDF/OpenAir_Manual.pdf)

Carslaw D C and Ropkins K 2012 Openair—an R package for air quality data analysis *Environ. Mod. Software* **27-28** 52–61

Chang K-L, Petropavlovskikh I, Copper O R, Schultz M G and Wang T 2017 Regional trend analysis of surface ozone observations from monitoring networks in eastern North America, Europe and East Asia *Elem. Sci. Anth.* **5** 50

Cohen A J *et al* 2017 Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015 *Lancet* **389** 1907–18

Van Der A R J, Mijling B, Ding J, Elissavet Koukouli M, Liu F, Li Q, Mao H and Theys N 2017 Cleaning up the air: effectiveness of air quality policy for SO_2 and NO_x emissions in China *Atmos. Chem. Phys.* **17** 1775–89

Feng L and Liao W 2016 Legislation, plans, and policies for prevention and control of air pollution in China: achievements, challenges, and improvements *J. Cleaner Prod.* **112** 1549–58

Fleming Z L *et al* 2018 Tropospheric ozone assessment report: present-day ozone distribution and trends relevant to human health *Elem. Sci. Anth.* **6** 12

Florig H K, Sun G and Song G 2002 Evolution of particulate regulation in China—prospects and challenges of exposure-based control *Chemosphere* **49** 1163–74

Fu G Q, Xu W Y, Yang R F, Li J B and Zhao C S 2014 The distribution and trends of fog and haze in the North China Plain over the past 30 years *Atmos. Chem. Phys.* **14** 11949–58

Fu Y, Tai A P K and Liao H 2016 Impacts of historical climate and land cover changes on fine particulate matter (PM2.5) air quality in East Asia between 1980 and 2010 *Atmos. Chem. Phys.* **16** 10369–83

Ghanem D and Zhang J 2014 Effortless perfection:' do Chinese cities manipulate air pollution data? *J. Environ. Econ. Manage.* **68** 203–25

Gu D, Wang Y, Smeltzer C and Liu Z 2013 Reduction in noxemission trends over China: regional and seasonal variations *Environ. Sci. Technol.* **47** 12912–9

Gu Y and Yim S H L 2016 The air quality and health impacts of domestic trans-boundary pollution in various regions of China *Environ. Int.* **97** 117–24

Guan D, Su X, Zhang Q, Peters G P, Liu Z, Lei Y and He K 2014 The socioeconomic drivers of China's primary PM2.5 emissions *Environ. Res. Lett.* **9** 024010

Han L, Zhou W and Li W 2016 Fine particulate (PM2.5) dynamics during rapid urbanization in Beijing, 1973-2013 *Sci. Rep.* **6** 23604

Huang D, Xu J and Zhang S 2012 Valuing the health risks of particulate air pollution in the Pearl River Delta, China *Environ. Sci. Policy* **15** 38–47

Irie H, Muto T, Itahashi S, Kurokawa J and Uno I 2016 Turnaround of tropospheric nitrogen dioxide pollution trends in China, Japan, and South Korea *Sola* **12** 170–4

Jin X and Holloway T 2015 Spatial and temporal variability of ozone sensitivity over China observed from the Ozone Monitoring Instrument *J. Geophys. Res.* **120** 7229–46

Jin Y, Andersson H and Zhang S 2016 Air pollution control policies in China: a retrospective and prospects *Int. J. Environ. Res. Public Health* **13** 1219

Kan H and Chen B 2004 Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment *Sci. Total Environ.* **322** 71–9

Klimont Z, Smith S J and Cofala J 2013 The last decade of global anthropogenic sulfur dioxide: 2000–2011 emissions *Environ. Res. Lett.* **8** 014003

Krotkov N A *et al* 2016 Aura OMI observations of regional SO_2 and NO_2 pollution changes from 2005 to 2015 *Atmos. Chem. Phys.* **16** 4605–29

Lelieveld J, Evans J S, Fnais M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale *Nat. Res.* **525** 367–71

Leung D M, Tai A P K, Mickley L J, Moch J M, Van Donkelaar A, Shen L and Martin R V 2018 Synoptic meteorological modes of variability for fine particulate matter (PM2.5) air quality in major metropolitan regions of China *Atmos. Chem. Phys.* **18** 6733–48

Li C *et al* 2017a Trends in chemical composition of global and regional population-weighted fine particulate matter estimated for 25 years *Environ. Sci. Technol.* **51** 11185–95

Li C *et al* 2017b India is overtaking china as the world's largest emitter of anthropogenic sulfur dioxide *Sci. Rep.* **7** 14304

Li Q, Zhang R and Wang Y 2016 Interannual variation of the wintertime fog-haze days across central and eastern China and its relation with East Asian winter monsoon *Int. J. Climatol.* **36** 346–54

Liang X, Li S, Zhang S, Huang H and Chen S X 2016 PM2.5data reliability, consistency, and air quality assessment in five Chinese cities *J. Geophys. Res.* **121** 10

Lin C Q, Liu G, Lau A K H, Li Y, Li C C, Fung J C H and Lao X Q 2018 High-resolution satellite remote sensing of provincial PM2.5trends in China from 2001 to 2015 *Atmos. Environ.* **180** 110–6

Ling Z, Huang T, Zhao Y, Li J, Zhang X, Wang J, Lian L, Mao X, Gao H and Ma J 2017 OMI-measured increasing SO_2 emissions due to energy industry expansion and relocation in northwestern China *Atmos. Chem. Phys.* **17** 9115–31

Liu F, Zhang Q, Tong D, Zheng B, Li M, Huo H and He K B 2015 High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010 *Atmos. Chem. Phys.* **5** 13299–317

Liu F, Zhang Q, Van Der A R J, Zheng B, Tong D, Yan L, Zheng Y and He K 2016a Recent reduction in NOx emissions over China: synthesis of satellite observations and emission inventories *Environ. Res. Lett.* **11** 114002

Liu J, Li W and Li J 2016b Quality screening for air quality monitoring data in China *Environ. Pollut.* **216** 720–3

Liu Y H, Liao W Y, Lin X F, Li L and Zeng X L 2017 Assessment of Co-benefits of vehicle emission reduction measures for 2015–2020 in the Pearl River Delta region, China *Environ. Pollut.* **223** 62–72

Lu Z, Streets D G, Zhang Q, Wang S, Carmichael G R, Cheng Y F, Wei C, Chin M, Diehl T and Tan Q 2010 Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000 *Atmos. Chem. Phys.* **10** 6311–31

Ma Z, Hu X, Huang L, Bi J and Liu Y 2014 Estimating ground-level PM2.5 in china using satellite remote sensing *Environ. Sci. Technol.* **48** 7436–44

Ma Z, Hu X, Sayer A M, Levy R, Zhang Q, Xue Y, Tong S, Bi J, Huang L and Liu Y 2016a Satellite-based spatiotemporal trends in PM2.5concentrations: China, 2004-2013 *Environ. Health Perspect.* **124** 184–92

Ma Z, Xu J, Quan W, Zhang Z, Lin W and Xu X 2016b Significant increase of surface ozone at a rural site, north of eastern China *Atmos. Chem. Phys.* **16** 3969–77

Peng J, Chen S, Lü H, Liu Y and Wu J 2016 Spatiotemporal patterns of remotely sensed PM2.5concentration in China from 1999 to 2011 *Remote Sens. Environ.* **174** 109–21

Rohde R A and Muller R A 2015 Air pollution in China: mapping of concentrations and sources *PLoS ONE* **10** e0135749

Sheehan P, Cheng E, English A and Sun F 2014 China's response to the air pollution shock *Nat. Clim. Change* **4** 306–9

Stoerk T 2016 Statistical corruption in Beijing's air quality data has likely ended in 2012 *Atmos. Environ.* **127** 365–71

Tao S *et al* 2018 Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey *Nat. Energy* **3** 567–73

Verstraeten W W, Neu J L, Williams J E, Bowman K W, Worden J R and Boersma K F 2015 Rapid increases in tropospheric ozone production and export from China *Nat. Geosci.* **8** 690–5

Wang L *et al* 2018 Taking action on air pollution control in the Beijing-Tianjin-Hebei (BTH) region: progress, challenges and opportunities *Int. J. Environ. Res. Public Health* **15** 306

Wang T, Wei X L, Ding A J, Poon C N, Lam K S, Li Y S, Chan L Y and Anson M 2009 Increasing surface ozone concentrations in the background atmosphere of Southern China, 1994–2007 *Atmos. Chem. Phys.* **9** 6217–27

Wang X, Chen W, Chen D, Wu Z and Fan Q 2016 Long-term trends of fine particulate matter and chemical composition in the Pearl River Delta Economic Zone (PRDEZ), China *Frontiers Environ. Sci. Eng.* **10** 53–62

Wu Y, Zhang S, Hao J, Liu H, Wu X, Hu J, Walsh M P, Wallington T J, Zhang K M and Stevanovic S 2017 On-road vehicle emissions and their control in China: A review and outlook *Sci. Total Environ.* **574** 332–49

Xia Y, Guan D, Jiang X, Peng L, Schroeder H and Zhang Q 2016 Assessment of socioeconomic costs to China's air pollution *Atmos. Environ.* **139** 147–56

Xu W, Lin W, Xu X, Tang J, Huang J, Wu H and Zhang X 2016 Long-term trends of surface ozone and its influencing factors at the Mt Waliguan GAW station, China: 1. Overall trends and characteristics *Atmos. Chem. Phys.* **16** 6191–205

Zhang Q, Geng G N, Wang S W, Richter A and He K B 2012 Satellite remote sensing of changes in NO_x emissions over China during 1996-2010 *Chin. Sci. Bull.* **57** 2857–64

Zhang X, Zhang W, Lu X, Liu X, Chen D, Liu L and Huang X 2018 Long-term trends in NO_2 columns related to economic developments and air quality policies from 1997 to 2016 in China *Sci. Total Environ.* **639** 146–55

Zhang Y-L and Cao F 2015 Fine particulate matter (PM2.5) in China at a city level *Sci. Rep.* **5** 14884

Zhao S, Zhang H and Xie B 2017 The effects of El niño-south oscillation on the winter haze pollution of China *Atmos. Chem. Phys* **185194** 1–24

Zheng B *et al* 2018 Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions *Atmos. Chem. Phys. Discuss.* **18** 1–27

Zheng Y, Xue T, Zhang Q, Geng G, Tong D, Li X and He K 2017 Air quality improvements and health benefits from China's clean air action since 2013 *Environ. Res. Lett.* **12**