Review

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Understanding sources of fine particulate matter in China

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Fine particulate matter has been a major concern in China as it is closely linked to issues such as haze, health and climate impacts. Since China released its new national air quality standard for fine particulate matter (PM_{2.5}) in 2012, great efforts have been put into reducing its concentration and meeting the standard. Significant improvement has been seen in recent years, especially in Beijing, the capital city of China. This paper reviews how China understands its sources of fine particulate matter, the major contributor to haze, and the most recent findings by researchers. It covers the characteristics of PM_{2.5} in China, the major methods to understand its sources such as emission inventory and measurement networks, the major research programmes in air quality research, and the major measures that lead to successful control of fine particulate matter pollution. A great example of linking scientific findings to policy is the control of coal combustion from the residential sector in northern China. This review not only provides an overview of the fine particulate matter pollution problem in China, but also its experience of air quality management, which may benefit other countries facing similar issues.

This article is part of a discussion meeting issue 'Air quality, past present and future'.

1. Introduction

PM_{2.5} (particles with aerodynamic diameter less than or equal to 2.5 µm) has been known to be closely linked to visibility reduction or haze; however, there was no standard for PM_{2.5} in China until 2012. Before that,

only the PM₁₀ (particles with aerodynamic diameter less than or equal to 10 µm) standard was available. Due to the increased concerns regarding air quality, health impacts and visibility, the standard of PM_{2.5} in China was introduced on February 29, 2012 (GB 3095–2012) by the State Environmental Protection Agency of China (State Environmental Protection Agency of China, 2012; [1]). This first national standard for PM_{2.5} was approved by China's State Council, thus China began its task of cleaning its air [2]. China adopts the World Health Organization (WHO) interim target-1 (IT-1) standard with the annual mean level of 35 µg m⁻³ and daily level of 75 µg m⁻³.

Since the release of the standard in 2012, China started its official monitoring of PM_{2.5} in 2013 and data are provided to the public (<https://www.aqistudy.cn/>). Based on the 2013 Report on the State of the Environment in China, among 74 cities in 2013, only 3 out of 74 meet the standard, indicating that there is an absolute need for China to set such a standard and regulate fine particulate matter concentration. The three cities are Haikou in Hainan Province, Zhoushan in Zhejiang Province and Lhasa in the Tibet Plateau. The severe haze that occurred in January 2013 is very famous and has been widely studied by domestic and international researchers. Two most severe episodes, which occurred during 9–15 January, 2013 and 25–31 January, 2013, were studied the most as they were characterized by large-scale, long-lasting and high concentration with the maximum hourly PM_{2.5} concentration in Beijing reaching 680 µg m⁻³ [3]. A series of studies, based on smog chamber, field observation and air quality models, were conducted to investigate the formation mechanisms, evaluate the impacts of heterogeneous chemistry on regional haze formation and assess the health-based economic costs linked to PM_{2.5} pollution [3–7].

About 32% of the world's population live in areas exceeding the WHO IT-1 standard (35 µg m⁻³ annually), while 83% of the Chinese population lives in regions exceeding the standard [8]. Most of the population in China is mainly distributed in grid cells with high PM_{2.5} concentration. A study by Liu *et al.* [8] provides an estimate that about 1.37 million premature mortalities in 2013 in China were associated with PM_{2.5} pollution.

2. Characteristics of particulate matter pollution

The fine particulate matter problem in China is different from other countries, with differences in emission sources, formation mechanisms and diffusion conditions, which are attributable to topographic and meteorological conditions. The characteristics of PM_{2.5} pollution in China are listed and discussed below.

(a) Multiple and complex emission sources in China

Sources of PM_{2.5} in China are not only multiple, but also complex. The natural sources primarily include sea salt, dust, forest and grassland fires, while anthropogenic sources include different kinds of industrial processes, power plants, vehicular exhaust, crop residue burning in the field and emissions from residential activities. Residential sources are very special in China as they include daily stir-frying cooking activity and large amounts of solid fuels including coal and biomass (e.g. crop residues and wood) burning in the residential sector for heating and cooking in rural China, especially during heating seasons. According to the bottom-up Multi-resolution Emission Inventory for China, the residential sector is the second biggest source of PM_{2.5}, with contributions of around 36–41% from the years 2010 to 2017 [9].

The industrial sector is identified as the most important emission source in China, accounting for an average of 50% of PM_{2.5} emissions during 2010–2017 [9,10]. It is worth noting that what is special about China is that it employs a very wide range of technology, from very low-tech based activities in poor and rural areas (e.g. cement plant) to very advanced technology applied in major industries in megacities (e.g. power plant) at the same time, making the PM_{2.5} pollution more complex and difficult to deal with.

(b) The co-existence of coal combustion and vehicular emissions

With the fast population growth in China, it is inevitable that energy consumption has increased along with it. In recent years, contributions from both motor vehicles and coal combustion emissions increased in China. In addition to a very high ambient concentration of fine particles, the coexistence of vehicular exhaust (Los Angeles type) and coal combustion (London type) makes the air pollution problem harder to tackle and more complex to understand in China.

(c) Quick change of particulate matter concentration in Beijing

Haze episodes frequently occur in fall and winter in Beijing, compared to summer and spring. In general, there are two typical types of haze. One type is fast increase within a few hours, and the other type is gradually built up over a few days [3]. An example is given of the first haze episode (from January 9–15) during January 2013. Within 8 h, $\text{PM}_{2.5}$ hourly concentration increased quickly from a level lower than $35 \mu\text{g m}^{-3}$ to a level higher than $500 \mu\text{g m}^{-3}$, which could hardly be seen in a city in any other country nowadays. The increase rate of $\text{PM}_{2.5}$ was $88 \mu\text{g m}^{-3}$ per hour. An example of a slow build-up case is the second episode of the same month (from January 25–30, 2013). The $\text{PM}_{2.5}$ concentration started at around $20 \mu\text{g m}^{-3}$ on January 25 and slowly reached about $500 \mu\text{g m}^{-3}$ on January 30, with an increase rate of $4 \mu\text{g m}^{-3}$ per hour [3]. Many studies focus on the discussion of why and how $\text{PM}_{2.5}$ can change so quickly for haze in China [4,5,11,12]. Some studies suggest special chemical mechanisms while some attribute it to regional transport.

Haze episodes in Beijing were found to exhibit a clear periodic cycle of about 4–7 days during fall and winter seasons [13,14]. The first paper that discussed a saw-tooth cycle of $\text{PM}_{2.5}$ concentration in Beijing is by Jia *et al.* [15]. $\text{PM}_{2.5}$ concentration in Beijing has shown quick changes with time with the strong asymmetric ‘sawtooth cycles’ from low to high $\text{PM}_{2.5}$ concentration [15]. It has an average duration of 5 days, which is controlled by synoptic cycles. $\text{PM}_{2.5}$ reaches a very low concentration when cold fronts pass Beijing. It is closely linked to meteorology with low concentration associated with dry and strong wind from the north of Beijing (wind speed usually higher than 5 m s^{-1}), and high concentration is often correlated with humid air and regional transport from the south of Beijing, especially Hebei Province. Hebei Province is known to have a high density of industrial emissions and activities. Several of its major cities, such as Shijiazhuang, Baoding and Langfang, are in the list of the most polluted cities in China.

(d) Haze dominated by secondary components and under high humidity

When chemical compositions of $\text{PM}_{2.5}$ in haze episodes were examined, it was found that secondary components (e.g. sulphate, nitrate, ammonia and secondary organic aerosol) dominated in most cases. Huang *et al.* [16] reported that the severe haze pollution event during January 2013 was driven primarily by secondary aerosol formation, which contributed 30–77% of $\text{PM}_{2.5}$ (average for four megacities including Beijing, Xi’an, Shanghai, and Guangzhou in the study). Other measurements confirm the role of the secondary species of $\text{PM}_{2.5}$ [17–20]. As haze often occurs under high relative humidity (RH), hygroscopic growth of particles is one of the major topics to investigate. Using data from 13 cities in China, Wang *et al.* [21] examined the impacts of meteorology on $\text{PM}_{2.5}$ concentration and found that RH usually reached up to 90–95% during the period of $\text{PM}_{2.5}$ peak, suggesting the important role of humidity in the extreme value of $\text{PM}_{2.5}$. This corresponds well to the findings that most of the time haze occurred when humid and polluted air masses were transported to Beijing during the later phase of haze formation [15].

(e) Clear spatial and seasonal variation

As China is under the influence of the Asian monsoon, most of the cities have shown a summer low and winter high seasonal variation pattern for $\text{PM}_{2.5}$ concentration. This is more obvious

in northern China because total emissions are stronger in the north, especially during the cold winter. Those activities for heating including power plants and residential heating using coal and biomass lead to higher emissions in winter especially in northern China.

With hourly data released by the Ministry of Environmental Protection of China, seasonal variations of $\text{PM}_{2.5}$ in 31 capital cities in China between March 2013 and February 2014 were examined by Wang *et al.* [22]. $\text{PM}_{2.5}$ levels in cities in the north region were higher than those in the west and the southeast regions. In most cases, the number of non-attainment days was the highest in winter; however, high pollution days were also frequently found in fall for the southeast region and in spring for the west region [22]. $\text{PM}_{2.5}$ concentrations retrieved by satellite data (the Moderate Resolution Imaging Spectroradiometer, MODIS) during 2004–2013 also confirm that summer is the cleanest season and winter is the most polluted season [23].

$\text{PM}_{2.5}$ concentration in China has a spatial pattern with a higher level in the north but lower level in the south. As most of the developed regions are in the east, it also has a clear high $\text{PM}_{2.5}$ concentration level in the east, with a low level in the west. The west regions include deserts and the Tibet Plateau. The population density and human activities are much higher in the east. The spatial distribution of $\text{PM}_{2.5}$ concentration is closely related to population density and gross domestic product (GDP). Besides the influence of source emissions, the large-scale meteorological impact on the spatial pattern of $\text{PM}_{2.5}$ pollution during winter was examined by Wang *et al.* [24].

The clear north high–south low pattern has been observed in China for years. A study by Chen *et al.* [25] indicated a stronger health impact in the north was due to higher particulate matter concentration. In their study, it is reported that ambient concentrations of total suspended particulate (TSP) were about $184 \mu\text{g m}^{-3}$ and 55% higher in the north and the analysis suggests that life expectancies in the north were about 5.5 years lower due to an increased incidence of cardiorespiratory mortality. A follow-up study examined PM_{10} and provided an estimate that 3.7 billion life-years would be saved if the Class I standard for PM_{10} could be met for all regions of China [26]. Health impacts due to high concentration of particulate matter in the north are certainly of great concern. Physical and chemical properties of $\text{PM}_{2.5}$, such as particle size and chemical composition, have been demonstrated to be two of the important factors responsible for $\text{PM}_{2.5}$ health effects [27,28]. A growing number of studies have recently been conducted focusing on the health effects of $\text{PM}_{2.5}$ components, which suggest that certain $\text{PM}_{2.5}$ components such as black carbon (BC), transition metals and organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and quinones-like substances may have relatively higher health impacts due to stronger toxicity or higher oxidative potential [28–31]. Therefore, this implies that although southern China has lower levels of $\text{PM}_{2.5}$ than northern China, it does not necessarily mean that the potential health risk of $\text{PM}_{2.5}$ in southern China is also lower.

Besides higher heating demand in the north, the high ambient concentration of fine particulate matter in northern China is also due to intense and active anthropogenic activities in the north including the industrial sector. Jin *et al.* [32] present the cartogram of the $\text{PM}_{2.5}$ emission map for each year in China during 2005–2014.

The chemical composition of $\text{PM}_{2.5}$ in China in published literature has been compiled by Zhang *et al.* [33]. Although it is from different studies (different seasons and methods etc.), it is clear that there are still some patterns. In northern China, especially the northwestern part, crustal materials are very important compared to the east and south. Crustal materials account for 48% of $\text{PM}_{2.5}$ in Waliguan, 45% in Xining and 18% in Xi'an [33]. Organics are about one third of $\text{PM}_{2.5}$, followed by sulphate, nitrate, and ammonium.

3. Plans to reduce particulate matter concentration in China

(a) Air pollution prevention and control action plan

In order to reduce $\text{PM}_{2.5}$ levels for a blue sky, the State Council of China has released its first national plan targeting $\text{PM}_{2.5}$ —Air Pollution Prevention and Control Action Plan during 2013–2017 on September 10, 2013 [34]. The air quality management of China has shifted from targeting

‘emission reduction’ (technology-based) to targeting ‘air quality’ (risk-based). The 5-year Plan set a target for lowering the PM_{2.5} level. However, the target for each region was set differently, with 25% reduction in the Jing-Jin-Ji area, 20% reduction in the Yangtze River Delta (YRD) area, 15% in the Pearl River Delta (PRD) area and an annual average of 60 µg m⁻³ for Beijing (The State Council of the People’s Republic of China, 2013 [34]). Under this national plan, each province or city makes its own detailed plans to achieve the goals set by the State Council. A series of stringent clean air actions focusing on industry, residential and transport sectors were implemented, including strengthening industrial and vehicle emission standards, promoting clean energy and fuels in residential and transport sectors, and phasing out small and high pollution factories and outdated industrial capacities [35]. The impacts of emission control measures on PM_{2.5} concentration reduction based on this national action plan have been evaluated by different studies from the aspects of emission inventory, field observation and air quality models [9,35–38]. For example, Zhang *et al.* [35] indicated that clean air actions on industrial and residential sectors were major effective measures in reducing PM_{2.5} and health burden.

(b) Current major air pollution research programmes in China

Along with the announcement of the Clean Air Action Plan, China’s funding agencies have launched several major air pollution programmes to investigate haze related scientific questions and provide scientific support for formulating control strategies. For example, the National Natural Science Foundation of China has a programme entitled ‘The formation processes, health impacts and response mechanism of air pollution complex in China’ with a funding level of 400 million Yuan from 2015–2022. A key research plan entitled ‘Air pollution formation mechanisms and control technology’ is supported by the Ministry of Science and Technology with a total funding level of 2.5 billion Yuan (from 2015 to 2020). A programme named the ‘Foundation of Prime Minister’ focuses on formation mechanisms and controlling policy on heavy air pollution (2017–2019) and it covers ‘2 + 26’ cities, with 2 referring to Beijing and Tianjin, and the other 26 cities including 8 cities in Hebei Province, 7 cities in Shandong Province, 7 cities in Henan Province and 4 cities in Shanxi Province.

4. Ways to understand sources of particulate matter in China

To understand sources in China, there are several major approaches, including ambient measurements combined with receptor models, emission inventory and three-dimensional air quality models (figure 1).

(a) By ambient measurements

Source apportionment with receptor model is often used for identifying sources with chemical tracers measured in ambient aerosols. Zhang *et al.* [33] compiled the results of PM_{2.5} source apportionment conducted in China and published in previous literature. It can be seen that vehicular exhaust, coal combustion, and secondary sources are identified as major sources of PM_{2.5}. Industrial and biomass burning are also important sources identified in some studies. In receptor models, the ‘secondary source’ is often lumped as one source type, and it is hard to apportion to specific source types, such as coal combustion. In China, there are some efforts to apportion the ‘secondary source’ into specific source types by incorporating with emission inventory information and air quality models.

Apart from receptor models, there are a variety of methods to identify sources based on ambient measurements. For example, dual carbon isotopes (¹⁴C and ¹³C) have been applied to identify sources for BC and organic carbon (OC) in PM_{2.5} [39–41]. The findings from these studies suggest that coal combustion is much more important in the north China Plain (NCP) compared to PRD and YRD. The biogenic contribution in YRD is higher than PRD and NCP, where the influence of biomass burning is relatively more significant. With this dual carbon

Figure 1. Major methods to identify and quantify sources of $\text{PM}_{2.5}$ in China. (Online version in colour.)

isotope technique, it is found that winter $\text{PM}_{2.5}$ in Beijing has a higher anthropogenic fossil source contribution compared to winter $\text{PM}_{2.5}$ in Shanghai. However, there are clear differences for source types between Beijing winter and summer, with more biogenic OC in summer.

It has been reported by a number of studies that haze in China is regional in most cases. Therefore, regional monitoring networks are essential to monitor and understand the problem. There are some regional networks in China including the network of the China Environmental Monitoring Center, the CARE-China network of the Chinese Academy of Sciences established late 2011 [42,43] and the China Aerosol Remote Sensing Network (CARSNET) established by the China Meteorological Administration (CMA) in 2002 [44].

In each city, there are tens of sites operated by the monitoring centre of the city with the data released to the public through their official websites. In recent years, with the improvement of technology, the sensor network has become available in China and is widely adopted in many cities. For example, there are currently 1500 sensors installed in Beijing with the major layout principles as even coverage, but high density in key areas. The species measured by these sensors include $\text{PM}_{2.5}$ and TSP. For the plain area in Beijing, each grid (3×3 km) has one sensor, while in the mountain area, there is an 8×8 km resolution. The sensor network by a company (Sailhero Inc.) includes 13 354 sites in 120 cities of 18 provinces. This company has installed 7082 sensors in Hebei, 1494 sensors in Henan, 654 sensors in Gansu and 458 sensors in Guangdong. The sensor network provides the quick and visible monitoring of air pollutants, such as $\text{PM}_{2.5}$, PM_{10} , nitrogen dioxide (NO_2), carbon oxide (CO), sulphur dioxide (SO_2), ozone (O_3) and total volatile organic compounds (TVOCs). The location of sensors is primarily based on the needs of the city; they could be installed at sites owned by the monitoring centre of the city, transportation hubs, key industry/enterprises and some special areas such as restaurants. However, there are very few publications about such sensor networks in China, although they have been widely used and operated in many cities. One example is the study by Shi *et al.* [45], who use the high-resolution sensor network measurement data in an urban city in north China to examine the spatial representativeness of ground stations. It was found that the representative area for a single station varies with locations, and it was less than 3 km^2 for more than half of the stations during the study period.

$\text{PM}_{2.5}$ species data from ambient monitoring, especially those with tracer power, are included in receptor models such as chemical mass balance (CMB) and positive matrix factorization (PMF) for

source apportionment studies. For CMB analysis, local source profiles are very important input; however, there is still very limited information in China at present, although a growing number of source testing work is ongoing. Zhang *et al.* [33] summarized the published PM_{2.5} source profiles in China.

Online source apportionment studies have been actively conducted in China in recent years. This is mostly due to two reasons. One is the fast change of PM_{2.5} concentration including various chemical species in fine PM_{2.5}. Another is the need to take quick actions or strategies, thus traditional offline analysis cannot meet the need. The major high-time resolution PM_{2.5} composition instruments include the Xact 625 ambient metal monitor by Cooper Environmental, the semi-continuous elemental and organic carbon (EC/OC) analyser by Sunset Lab Inc., the online water-soluble ions monitoring system, the online Single Particle Aerosol Mass Spectrometer (SPAMS) by Hexin Analytical Instrument Co., Ltd. and Aerosol Mass Spectrometry (AMS) by Aerodyne Research Inc. The online source apportionment of PM_{2.5} has been actively carried out in China in recent years, with various instruments such as Xact [46–48], SPAMS [49–51] and AMS [52]. Among them, AMS primarily focuses on source apportionment of organic aerosols. The challenges and perspectives of online source apportionment were summarized by Zheng *et al.* [53]. There are some major challenges associated with the source apportionment study. For example, a single method is often used for a specific study, and a full assessment of the differences among methods and inter-comparison are lacking. Thus, knowing how to evaluate the accuracy of source apportionment results is very important. Another major challenge is that often the receptor method has a source category known as the ‘secondary source’ which mainly includes sulphate, nitrate and ammonium as the major species in this source category or factor. However, how to apportion this ‘secondary source’ into specific source types such as coal combustion and vehicular exhaust is still a challenge. Some efforts have been made to solve this problem by using emission inventory information or integration with results from air quality models. Some chamber aging studies focusing on gasoline and diesel vehicles, biomass burning and cooking have been conducted in China, in which primary emissions of particles and gaseous precursors, especially organic compounds such as VOCs, intermediate-volatility organic compounds (IVOCs) and semi-volatile organic compounds (SVOCs), have been measured and their aging processes investigated [54–58]. With more information from chamber studies, it will be possible to apportion the ‘secondary source’ into specific source types in the near future.

Tracers, both organic and inorganic, are the key to identifying sources of air mass and are responsible for accurate source apportionment results. As fuel, energy structure and emission sources in China are very different from other countries, some tracers that have been widely used in other countries may not be applicable to this region. A study by Yu *et al.* [59] examined whether potassium could be used as an effective tracer for biomass burning source in Beijing. This is because in some studies in China, K⁺ concentration is not measured, and only K data are available to be used in CMB or PMF for source apportionment studies. It is clear that coal combustion is one of the major sources of K in Beijing (about 69% in winter) as coal is still widely used in China, especially from residential sectors of rural areas. Levoglucosan is an organic tracer often used for pinpointing biomass burning sources [60]. Yan *et al.* [61] examined if residential coal combustion could be a source for levoglucosan in China and found a non-negligible contribution from coal combustion to ambient levoglucosan in Beijing during winter. Source tests indicated that low-temperature residential coal combustion could emit levoglucosan with emission factors ranging from 0.3 to 15.9 mg kg^{−1}. This is very important information because otherwise biomass burning source contribution could be overestimated.

(b) By emission inventory

Emission inventories developed by two teams are widely used by the community, and are available for researchers all over the world. The multi-resolution emission inventory for China (MEIC) was primarily developed by the team at Tsinghua University. The MEIC team released an Asian Emission Inventory, which covers ten air pollutants and greenhouse gases (e.g. SO₂,

NO₂, CO, non-methane volatile organic compounds (NMVOCs), ammonia (NH₃), PM₁₀, PM_{2.5}, BC, OC and CO₂) with a resolution of 0.25 degrees from 1990 to 2015. And the MEIC model contributes to the national emission guidelines in China. This emission inventory provides model-ready emissions for chemical transport and climate models. Emission data are available through application from the website (<http://meicmodel.org/users.html>).

Based on the MEIC emission inventory, SO₂ had a decreasing trend in China, with a sharp decrease from 2005 to 2010 and the major sectors were industry and power. Other pollutants showing a decreasing trend include nitrogen oxides (NO_x), CO, BC, primary OC and primary PM_{2.5}, especially from 2010. NH₃ shows a slight increase since 2000, while CO₂ and NMVOCs exhibit an increase since 2000 and have kept at a relatively constant level since 2010.

Some specific emission inventories are available in recent years in response to specific needs. For example, as Beijing, a megacity and the capital of China, has experienced a severe air pollution problem in recent years, a high-resolution emission inventory for Beijing has been developed [62]. The China power emission database (CPED) is also available with detailed information for pollutants such as SO₂ [63].

Another team led by Prof. Shu Tao from Peking University developed a global emission inventory including 97 source categories, 27 pollutants, and 224 countries with a spatial resolution (0.1 × 0.1 degree) from 1960 to 2014 (<http://inventory.pku.edu.cn>). The pollutants include PM_{2.5}, CO₂, BC, NO_x, Hg and NH₃. One of the distinctive characteristics of this emission inventory is that it has detailed information on PAHs. For example, based on this emission inventory, the estimated major sources of PAHs that pose health risks include fossil fuel, residential biomass burning and coke production [64–66].

(c) By modelling

The air quality model has been used as one of the major tools to understand sources in ambient atmosphere. The Nested Air Quality Prediction Modeling system (NAQPMS) is one of the models that is currently widely used in cities in China, developed by the team of Chinese scientists (with the key developer as Prof. Zifa Wang) from the Institute of Atmospheric Physics, Chinese Academy of Sciences [11,48,67,68]. Other models, such as the Community Multiscale Air Quality (CMAQ) model, are also widely used for source apportionment studies to identify source types and contributions as well as distinguishing local and regional contributions to PM_{2.5} [69,70].

5. Effective measures for air quality improvement in Beijing

(a) A review of the past 20 years

The United Nations Environment Programme (UNEP) recently released two technical reports with one entitled ‘A Review of Air Pollution Control in Beijing: 1998–2013’ [71] and the other entitled ‘A Review of 20 Years’ Air Pollution Control in Beijing’ [72], which provide detailed information on how China has improved its air quality, especially the major measures and implementation timetable of vehicle emissions and coal combustion emissions. From 2013 to 2017, in just five years, fine particle concentration has been quickly reduced by 35% in Beijing and 25% in the surrounding region and no other city has achieved such success within a few years [72]. The annual PM_{2.5} concentration in Beijing has dropped from about 90 µg m⁻³ in 2013 to about 60 µg m⁻³ in 2017. Zheng *et al.* [9] list the major clean air policies from 2010–2017 for four sectors including the power, industry, residential and transportation sectors. Over the past 20 years (1998–2018), with increased GDP and motor vehicle numbers, the ambient concentrations of SO₂, PM₁₀, and NO₂ in Beijing have decreased by 92%, 52% and 41%, respectively (Baoxian Liu, personal communication). This achievement in air quality improvement is accompanied by large investment in funding to clean up the air, from 1.7 billion Yuan in 2009 to 18.22 billion Yuan in 2017, increased by about 10 times within 8 years [72]. The PM_{2.5} concentration in Beijing has a clean spatial distribution with high in the south and low in the north. From 2013 to 2018, it can

Figure 2. Significant reduction of $PM_{2.5}$ concentration in China due to the Air Pollution Prevention and Control Action Plan (2013–2017) in three major areas including Jing-Jin-Ji (JJJ), YRD and PRD [35,73]. (Online version in colour.)

be seen that not only has $PM_{2.5}$ concentration decreased significantly, but also that the gradient between the north and south of Beijing has been reduced.

The effectiveness of various measures is assessed (figure 2). Cheng *et al.* [73] provided a quantified estimate for mobile source emissions and emission reduction effects of control measures in Beijing (1998–2017) and concluded that for pollutants such as CO, total hydrocarbon (THC), NO_x and $PM_{2.5}$, the most effective policy was phasing out older vehicles, followed by tightening emission standards. They also reported that the leading measure that contributes the most to pollutant emission reduction in Beijing (2013–2017) was control of coal-fired boilers for SO_2 , vehicle emission control for NO_x and management of residential burning for primary $PM_{2.5}$.

(b) From science to policy

During the process of air pollution control, the link between scientific findings and policy making is strengthened. A good example is residential coal control policy. Liu *et al.* [76] point out that the air pollutant emissions from Chinese households is a major and underappreciated ambient pollution source. In Beijing, Tianjin and Hebei Province area, more than 50% of emissions for primary $PM_{2.5}$, BC and OC are from the residential sector during wintertime (i.e. December, January and February). The study estimates the level of ambient $PM_{2.5}$ concentration reduction if residential emissions were removed. Other research groups also show similar findings and suggest the importance of cleaning up air and improving air quality by targeting the residential sector [77–79]. The study by Zheng *et al.* [9] provides an estimate of BC emissions in China from 2010 to 2017, and the residential sector is the largest contributor, followed by the industrial and transportation sectors.

With the support and suggestions from the scientific community, Beijing has adopted a policy to reduce emissions from residential coal combustion. It has proven to be an effective policy as can be seen from the clear reduction of sulphate in $PM_{2.5}$ in winter 2017 compared to that of winter 2016 in Beijing. After 2017, during wintertime, the major composition of $PM_{2.5}$ has shifted from sulphate-dominance to nitrate-dominance [80], indicating the effectiveness of controlling coal combustion and the increased importance of vehicular emissions, especially diesel vehicles. Therefore, in the future, Beijing may pay more attention to controlling emissions from heavy-duty diesel vehicles. Besides its impact on air quality, another major concern for emissions from coal combustion is its health impact [81]. The success in reduction of $PM_{2.5}$ from coal combustion to some extent will lead to substantial health benefits although attention should still be paid to controlling emissions from coal combustion in the future.

Recently, some suggestions such as controlling NH_3 emission have been proposed. A study by Liu *et al.* [82] indicates that ammonia emission control in China would help to mitigate haze and reduce nitrogen deposition to the ecosystem, but it will worsen acid rain. Therefore, the authors suggest different strategies should be applied for each region, with the priorities for northern China being controlling SO_2 , NO_x and NH_3 from agriculture, and the priorities for southern China and Sichuan Basin being controlling SO_2 and NO_x . Whether controlling NH_3 emissions is an effective approach has been actively discussed and investigated recently. It is also suggested that there are potential additional urban sources of NH_3 that contributes to high NH_3 levels in the city [83]. In addition, Liu *et al.* [84] proposes that there are rapidly growing emissions from ocean-going vessels in East Asia, which contribute a significant amount of air pollutants and CO_2 and suggest that attention should be paid to controlling specific source category in the future. Furthermore, recent studies have shown that ozone concentration has an increasing trend, although $\text{PM}_{2.5}$, NO_2 and SO_2 have been successfully reduced in recent years in China [75,85].

Data accessibility. This article has no additional data.

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