Journal of Cleaner Production 112 (2016) 1519–1527

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Air pollution and control action in Beijing

Hefeng Zhang [a], Shuxiao Wang [b], Jiming Hao [b], Xinming Wang [c], Shulan Wang [a, *], Fahe Chai [a, *], Mei Li [d]

[a] Atmospheric Environment Institute, Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
[b] School of Environment, State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing, 100084, China
[c] State Key Laboratory of Organic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, China
[d] Atmosphric Environment Institute of Safety and Pollution Control, Jinan University, Guangdong, 510632, China

ARTICLE INFO

Article history:
Received 17 March 2015
Received in revised form
11 April 2015
Accepted 13 April 2015
Available online 1 May 2015

Keywords:
Air pollution
Control action
Air quality standard
Policy and regulation
Beijing

ABSTRACT

Beijing, the capital of China, has experienced rapid industrialization, urbanization and motorization in recent decades. Consequently, air pollution in Beijing, especially fine particulate matter ($PM_{2.5}$) pollution, has gradually become a severe environmental issue, due to the continuing growth in energy consumption and the resulting multiple pollutant emissions. In response to the increasingly serious $PM_{2.5}$ pollution, Beijing's government implemented a series of policies, measures and regulations on air pollution prevention and control and took some concrete actions to improve air quality. In this paper, firstly, we summarize China's ambient air quality standards, China's policies and regulations on air pollution prevention and control. Secondly, we illustrate historical evolution and current status of air pollution in Beijing. Finally, we introduce control measures and actions in Beijing and its surrounding areas. The paper aims to help environmental scientists and policy makers around the world understand the past and current air pollution in Beijing and control strategies and actions taken by Beijing's government.

1. Introduction

Over the past three decades, China has experienced rapid economic growth and ranked the position as the world's second largest economy. In 2013, the gross domestic product (GDP) reached 56.8 trillion RMB (~9.2 trillion US dollars) and the resulting total energy consumption was equivalent to 3.75 billion tons of coal (see Fig. 1). For the year 2013, fossil fuel consumption (coal and oil) was estimated to account for more than 88% of total energy consumption (Chinese National Bureau of Statistics, 2013). Fossil fuel consumption is the dominant emission contributor of anthropogenic air pollutants in China, which was reported in recent studies (Chan and Yao, 2008; Zhao et al., 2011; Wang et al., 2012). Therefore, along with fossil fuel consumption, air pollution has become one of key environmental issues in China, with which Chinese government will have to cope in the coming decades (Zhang et al., 2012).

In recent years, air pollution, especially fine particulate matter ($PM_{2.5}$) pollution, has become a serious environmental problem in

* Corresponding authors.
E-mail addresses: wangsl@craes.org.cn (S. Wang), chaifh@craes.org.cn (F. Chai).

http://dx.doi.org/10.1016/j.jclepro.2015.04.092
0959-6526/© 2015 Published by Elsevier Ltd.

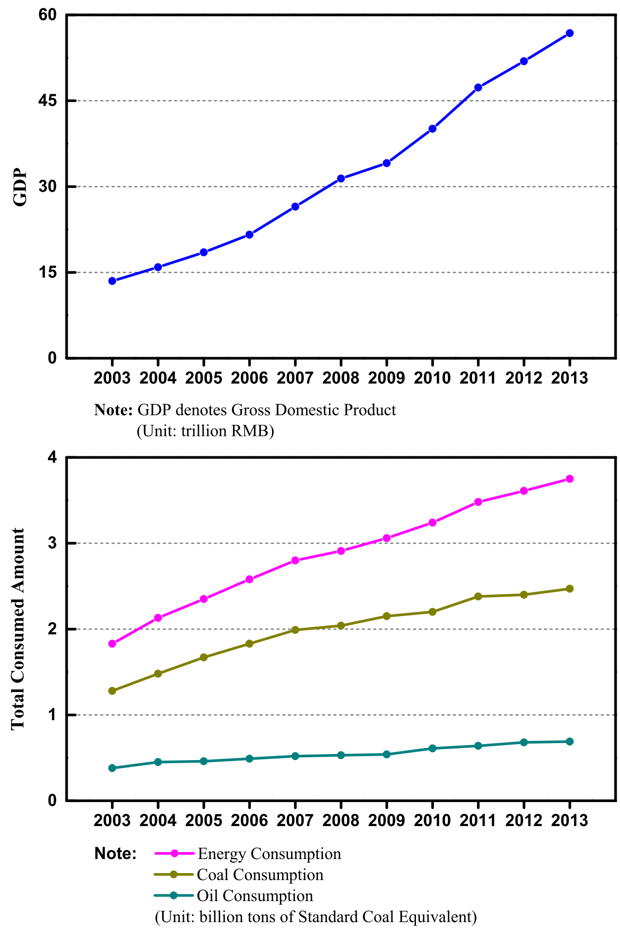

Fig. 1. Growth trends in GDP, energy consumption, coal consumption and oil consumption in China, 2003–2013. Data are from Chinese National Bureau of Statistics, 2013–2013 (http://www.stats.gov.cn/tjsj/ndsj).

China's economically well-developed regions (Hu et al., 2014), such as Beijing-Tianjin-Hebei region, Yangtze River Delta region, and Pearl River Delta region, which not only influence regional and urban air quality but also has an adverse impact on human health and eco-environment (Brunekreef and Holgate, 2002; Nel, 2005; Li et al., 2011; Kan et al., 2012; Dominici et al., 2014; Li et al., 2014). For example, in January 2013, extremely severe and persistent haze pollution happened in Central, Northern and Eastern China, with high concentrations of $PM_{2.5}$ (sometimes $PM_{2.5}$ record-breaking) covering about 1.3 million km^2 and affecting approximately 800 million people (Huang et al., 2014). Since then, Chinese government has recognized that it is a key task to prevent and control air pollution in China. Correspondingly, a series of policies, regulations and laws on prevention and control of air pollution have been formulated and promulgated. For instance, to effectively improve regional and urban air quality in China, ‘Action Plan on Prevention and Control of Air Pollution’ (hereinafter referred to as Action Plan) was implemented in September 2013, which proposed the targets that by 2017, $PM_{2.5}$ concentrations in Beijing-Tianjin-Hebei region, Yangtze River Delta region, and Pearl River Delta region should be declined by 25%, 20%, and 15%, respectively. In addition to improving regional air quality, the Action Plan put forward the clear requirement for Beijing's air quality improvement that by 2017, annual average $PM_{2.5}$ levels should be kept within 60 μg m^{-3}.

Beijing (39°56′N, 116°20′E), the capital of China, is located on the northwest of Beijing-Tianjin-Hebei region, which is surrounded by the Yanshan Mountain in the west, north and northeast directions. In recent decades, with the rapid development of industrialization, urbanization and motorization (Han et al., 2014), Beijing's energy consumption and the resulting multiple pollutant emissions were increasing year by year, which had adverse impacts on air quality, human health and eco-environment (Li et al., 2011, 2014). In recent years, particulate pollution, especially high concentrations of $PM_{2.5}$ pollution, have been the foremost problem of Beijing's air pollution (Hu et al., 2014). In order to lower $PM_{2.5}$ pollution and improve air quality, Beijing's government had taken a series of strict control actions to prevent and control air pollution, which, to a large extent, set a good example for other urban air quality improvement in China and even in other countries around the world. Therefore, it is necessary to make a brief introduction about Beijing's air pollution and control actions taken by Beijing's government.

In this paper, we review recent advances about China's ambient air quality standards, policies and regulations on air pollution prevention and control in China, illustrate historical evolution and current status of Beijing's air pollution, and present control measures and actions taken by Beijing's government. This review is not intended to be exhaustive but to make a preliminary introduction about Beijing's air pollution and control action. Moreover, the information included in this review is limited to the official data published before 2014.

2. Ambient air quality standards, policies and regulations on prevention and control of air pollution in China

2.1. Ambient Air Quality Standards (AAQR) in China

Ambient Air Quality Standards (AAQS) in China were originally formulated in 1982 (Fig. 2), which was the first official document aiming to improve ambient air quality. The first amendment of AAQR was implemented in 1996, which included three Grade standards (I, II and III) and recommended the limit values of seven principal pollutants (SO_2, NO_x, NO_2, CO, O_3, PM_{10} and TSP) (See Table 1). The second amendment was made in 2000, which removed the standard of NO_x pollutant and relaxed the limit values of NO_2 (Grade II) and O_3 (Grade I and II) (See Table 2). In February 2012, the third amendment was made by Ministry of Environmental Protection (MEP), which added the standards of $PM_{2.5}$ and Max. 8-h O_3 pollutants and tightened the guideline values of NO_2 (Grade II and Grade I – 1-hr) and PM_{10} (Grade II – annual) (See Table 3). In the newly amended AAQR, the guideline values of Max. 8-h O_3, daily- $PM_{2.5}$ and annual-$PM_{2.5}$ are 100, 35 and 15 μg m^{-3} for

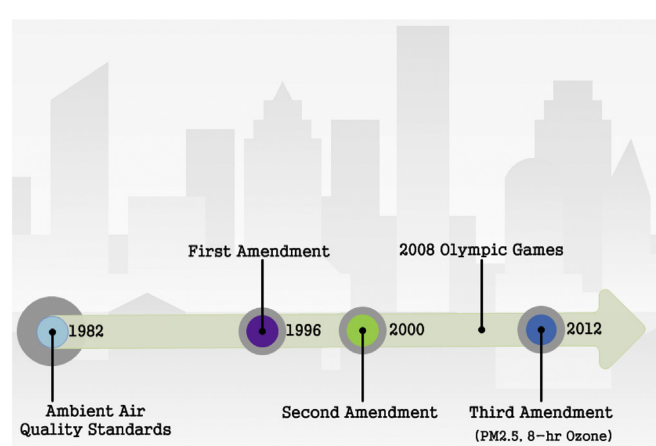

Fig. 2. Historic evolution of ambient air quality standards in China.

Table 1
National ambient air quality standards in china (GB3095-1996, first amendment).

		NAAQS guideline value (GB3095-1996)			Unit
		Grade-I	Grade-II	Grade-III	
SO_2	1-hr	150	500	700	$\mu g\ m^{-3}$
	Daily	50	150	250	
	Annual	20	60	100	
NO_x	1-hr	150	150	300	$\mu g\ m^{-3}$
	Daily	100	100	150	
	Annual	50	50	100	
NO_2	1-hr	120	120	240	$\mu g\ m^{-3}$
	Daily	80	80	120	
	Annual	40	40	80	
CO	1-hr	10	10	20	$mg\ m^{-3}$
	Daily	4	4	6	
O_3	1-hr	120	160	200	$\mu g\ m^{-3}$
PM_{10}	Daily	50	150	250	$\mu g\ m^{-3}$
	Annual	40	100	150	
TSP	Daily	120	300	500	$\mu g\ m^{-3}$
	Annual	80	200	300	

Grade-I standard and 160, 75 and 35 $\mu g\ m^{-3}$ for Grade-II standard, respectively, among which, $PM_{2.5}$ Grade-II standard is in consistent with the World Health Organization's (WHO) recommended interim target-I standard and $PM_{2.5}$ Grade-I standard agrees well with U.S. recommended guideline values of $PM_{2.5}$ (See Table 4).

2.2. Joint Prevention and Control of Air Pollution

In May 2010, 'Joint Prevention and Control of Air Pollution' was issued by the State Council of China, which is the first comprehensive policy document aiming to improve regional and urban air quality in China. This document designated three 'key regions' and six 'city clusters' to implement joint prevention and control of regional air pollution. Three 'key regions' are the Beijing-Tianjin-Hebei region, the Yangtze River Delta region and the Pearl River Delta region and Six 'city clusters' are central Liaoning, Shandong Peninsula, Wuhan and its surrounding area, Changsha-Zhuzhou -Xiangtan region, Chengdu-Chongqing region, and western coast of Taiwan Straits. This document also identified the key pollutants (such as SO_2, NO_x, PM and VOCs) of joint prevention and control of regional air pollution. In order to address acid rain, haze and photochemical smog pollution, the document proposed to establish the mechanism of unified planning, unified monitoring, unified supervision, unified evaluation and unified coordination for the joint prevention and control of regional air pollution.

In order to integrate environmental protection with economic development, 'Joint Prevention and Control of Air Pollution' proposed to insist on the following basic principles: (1) Optimizing structure and layout of regional industry. (2) Intensifying efforts to control key pollutants. (3) Strengthening cleaner use of energy. (4) Intensifying efforts to control vehicle pollution. (4) Improving supervision system of regional air quality. (5) Reinforcing support ability of air quality improvement. (6) Intensifying organization and coordination. These principles indicated that environmental management of regional air quality will be paid more attention from then on in China.

2.3. Action Plan on Prevention and Control of Air Pollution

In order to improve air quality and reduce heavy pollution in China, on 12 September 2013, 'Action Plan on Prevention and Control of Air Pollution' was issued by China's State Council, which would serve as the guidance for national efforts to prevent and control air pollution. The specific target of the Action Plan is that by 2017, PM_{10} concentrations will be declined by at least 10% compared to 2012 levels in Chinese urban areas, and $PM_{2.5}$ concentrations will be dropped by 25%, 20% and 15% in the Beijing-

Table 2
National ambient air quality standards in China (GB3095-2000, second amendment).2

		NAAQS Guideline Value (GB3095-2000)			Unit
		Grade-I	Grade-II	Grade-II	
SO_2	1-hr	150	500	700	
	Daily	50	150	250	$\mu g\ m^{-3}$
	Annual	20	60	100	
NO_2	1-hr	120	**240**	240	
	Daily	80	**120**	120	$\mu g\ m^{-3}$
	Annual	40	**80**	80	
CO	1-hr	10	10	20	$mg\ m^{-3}$
	Daily	4	4	6	
O_3	1-hr	**160**	**200**	200	$\mu g\ m^{-3}$
PM_{10}	Daily	50	150	250	$\mu g\ m^{-3}$
	Annual	40	100	150	
TSP	Daily	120	300	500	$\mu g\ m^{-3}$
	Annual	80	200	300	

Note: the blue color denotes the revised value

Table 3
National ambient air quality standards in China (GB3095-2012, third amendment).3

		NAAQS Guideline Value (GB3095-2012)		Unit
		Grade-I	Grade-II	
SO_2	1-hr	150	500	$\mu g\ m^{-3}$
	Daily	50	150	
	Annual	20	60	
NO_2	1-hr	**200**	**200**	$\mu g\ m^{-3}$
	Daily	80	**80**	
	Annual	40	**40**	
CO	1-hr	10	10	$mg\ m^{-3}$
	Daily	4	4	
O_3	1-hr	160	200	$\mu g\ m^{-3}$
	Max. 8-hr	**100**	**160**	
PM2.5	Daily	**35**	**75**	$\mu g\ m^{-3}$
	Annual	**15**	**35**	
PM10	Daily	50	150	$\mu g\ m^{-3}$
	Annual	40	**70**	

Note: the blue color denotes the revised value, the red color denotes the newly added value

Tianjin-Hebei, the Yangtze River Delta and the Pearl River Delta region, respectively. It is worth noting that the Action Plan requires that annual average $PM_{2.5}$ concentrations in Beijing must keep within 60 $\mu g\ m^{-3}$.

To achieve the above targets, the Action Plan defines the following 'ten measures': (1) Intensifying integrated control efforts and reducing multiple-pollutants emissions. (2) Optimizing industrial structure and promoting industrial upgrade. (3) Accelerating technological transformation and improving innovation capability. (4) Adjusting energy structure and increasing clean energy supply. (5) Strengthening 'energy-saving and environment-friendly' access threshold and optimizing industrial layout. (6) Playing the role of market mechanism and improving environmental economic policies. (7) Improving environmental law and regulation system and implementing supervision and management based on law and regulation. (8) Establishing regional coordination mechanism and making overall arrangement for regional environmental management. (9) Establishing monitoring, warning and emergency response system and coping with heavy pollution weather. (10) Clarifying responsibilities of government, enterprise, and society and mobilizing the public to participate in environmental protection.

2.4. Action Plan of Prevention and Control of Air Pollution in Beijing — Tianjin — Hebei region and surrounding area

On 17 September 2013, Implementation Rules of 'Action Plan on Prevention and Control of Air Pollution in Beijing-Tianjin-Hebei Region and Surrounding Area' (hereinafter referred to as Implementation Rules) was issued by China's Ministry of Environmental Protection (MEP). The specific target of the Implementation Rules is that by 2017, $PM_{2.5}$ concentrations compared to 2012 levels will be dropped by 25%, 20%, and 10% in Beijing-Tianjin-Heibei region, Shanxi-Shandong Region, and Inner Mongolia Autonomous Region, respectively, among which, annual average $PM_{2.5}$ concentrations in Beijing are required to be kept within 60 $\mu g\ m^{-3}$. Moreover, the key tasks of the Implementation Rules included: (1) Implementing integrated control and intensifying synchronous emission reduction of multi-pollutants, (2) Making overall arrangement for urban traffic management and controlling vehicle pollution, (3) Adjusting industrial structure and optimizing regional economic layout, (4) Controlling total amount of coal consumption and promoting high-efficiency clean usage of conventional energy, (5) Strengthening basic abilities of monitoring, warning, and emergency response system, (6) Intensifying organization and leadership and

Table 4
PM2.5 guideline values of National Ambient Air Quality Standards (NAAQS) in China, World Health Organization (WHO), United State (US) and European Union (EU).

		China (2012)		WHO (2005)			US (2006)	EU (2008)
		Grade-I	Grade-II	Target I	Target II	Target III		
$PM_{2.5}$	Daily	**35**	**75**	**75**	50	37.5	**35**	25
	Annual	**15**	**35**	**35**	25	15	**15**	20

The bold is to illustrate that $PM_{2.5}$ Grade-II value in China is consistent with WHO Target I and $PM_{2.5}$ Grade-I value in China is comparable with US guideline. It suggested that the guideline value of NAAQS in China was not the most stringent in the world.

reinforcing supervision and assessment. Additionally, the Implementation Rules also played an essential role in guaranteeing good air quality for APEC Economic Leader's Meeting held in Beijing in November 2014.

3. Air pollution in Beijing

In recent decades, urban air pollution gradually became a serious environmental issue in China (Shao et al., 2006; Parrish and Zhu, 2009), which not only resulted in air quality degradation, visibility impairment and health damage (Brunekreef et al., 2002; Nel, 2005; Kan et al., 2012) but also cut down the happiness feeling of urban inhabitants. Beijing, the capital of China, has experienced rapid motorization in the last two decades (Wu et al., 2011). By the end of 2013, Beijing's total vehicle population reached 5.43 million (http://zhengwu.beijing.gov.cn/tjxx/tjgb/t1340447). The growth in vehicle populations and the resulting exhaust emissions would have substantial impacts on urban air quality. Correspondingly, many studies have confirmed that urban air pollution in Beijing has shifted from being dominated by coal burning to a mix of coal burning and vehicle emissions (Wu et al., 2011; Wang and Hao, 2012). As a result, particulate pollution, especially $PM_{2.5}$ pollution, has become the major environmental problem that is influencing Beijing's air quality. For example, in January 2013, extremely severe haze pollution happened in Beijing and lasted for nearly the whole month, which was characterized by high concentrations of $PM_{2.5}$. In the following Sections 3.1 and 3.2, we made a brief introduction about historical evolution and current status of Beijing's air pollution.

3.1. Historical evolution of air pollution in Beijing

3.1.1. PM_{10} variation trends in Beijing (1998–2013)

Annual average concentrations of PM_{10} in Beijing steadily decreased from 188 μg m^{-3} in 1998 to 108 μg m^{-3} in 2013 as shown in Fig. 3, which were still higher than the limit value of 70 μg m^{-3} (Grade II) of China's AAQS for PM_{10}. As of 2013, annual average concentrations of PM_{10} in Beijing were 1.5 times higher than China's AAQS Grade-II standard, suggesting that PM_{10} pollution was a serious problem in Beijing (Zhang et al., 2011). In addition, it can be concluded from Fig. 3 that from 2008 through 2013, the $PM_{2.5}$/PM_{10} ratio in Beijing increased from 0.61 in 2008 to 0.82 in 2013, indicating that particulate pollution was mainly dominated by $PM_{2.5}$ pollution in Beijing. That is, $PM_{2.5}$ has ranked as Beijing's principal air pollutant.

3.1.2. SO_2 and NO_x variation trends in Beijing (1998–2013)

Annual average concentrations of SO_2 and NOx in Beijing dropped from 121 μg m^{-3} in 1998 to 27 μg m^{-3} in 2013 and from 74 μg m^{-3} in 1998 to 56 μg m^{-3} in 2013, respectively (Fig. 3). In 2013, SO_2 was much lower than the guideline value of 60 μg m^{-3} of China's AAQS Grade-II standard and comparable with the level of 20 μg m^{-3} of China's AAQS Grade-I standard, indicating that SO_2 emission control have been proven to be successful in Beijing (Zhao et al., 2013; Wang et al., 2014). In comparison, NOx emission control was not so good in Beijing. For the year 2013, NOx was 1.4 times higher than the limit value of 40 μg m^{-3} of China's AAQS (Grade I and II), indicating that NOx pollution in Beijing was still quite severe. It can be seen from Fig. 3 that NOx reduction was not obvious from 2008 through 2013 in Beijing, which might be explained by the fact that the increase of vehicle emissions counteracted the reduction of coal-burning emissions.

3.1.3. $PM_{2.5}$ variation trends in Beijing (2008–2013)

As described in Section 2.1, China's AAQS for $PM_{2.5}$ were issued in 2012. That is, before 2012, $PM_{2.5}$ was not listed as the standard pollutant in China's AAQS. Accordingly, no official $PM_{2.5}$ data was recorded in Beijing. Since 2013, Beijing's official $PM_{2.5}$ data was released and the annual average value of Beijing's $PM_{2.5}$ was 89.5 μg m^{-3} for the year 2013. The detailed information about Beijing's $PM_{2.5}$ monitoring can be obtained in http://zx.bjmemc.com.cn/. In addition to official $PM_{2.5}$ data, U.S. Embassy provided the annual average value of $PM_{2.5}$ in the period 2008 to 2013 as shown in Fig. 3. Based on the data measured by U.S. Embassy (http://beijing.usembassy-china.org.cn/), $PM_{2.5}$ in Beijing increased from 85 μg m^{-3} in 2008 to a peak of 104 μg m^{-3} in 2010 and then fallen to 91 μg m^{-3} in 2012 (see Fig. 3). However, in 2013, $PM_{2.5}$ again increased to 102 μg m^{-3}, which was a little different from the official value of 89.5 μg m^{-3} released by Beijing's Environmental Protection Bureau (EPB). This happened partly because different $PM_{2.5}$ monitoring instrument were employed by U.S. Embassy and Beijing's EPB. Besides, annual $PM_{2.5}$ concentrations provided by Beijing's EPB were the average values of 35 monitoring sites, which were distributed in Beijing's urban, suburb, and rural areas, while $PM_{2.5}$ measured by U. S. Embassy was the value of one monitoring site located in Beijing's urban area (Fig. 4). Although annual $PM_{2.5}$ levels measured by U.S. Embassy and Beijing's EPB were different,

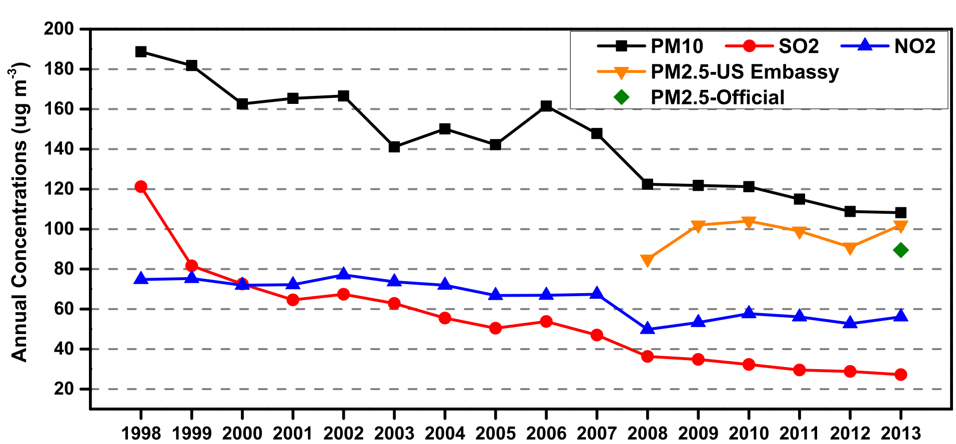

Fig. 3. Evolution trends of air pollutants in Beijing (annual values, unit: μg m^{-3}). Data source: PM_{10}, SO_2 and NO_2 are from Beijing Municipal Environmental Protection Bureau, 1989–2013, (http://www.bjepb.gov.cn/). PM2.5-U S Embassy is from Embassy of the United States, 2008–2013, (http://beijing.usembassy-china.org.cn/070109 air.html). PM2.5-Official is from Beijing Municipal Environmental Protection Bureau, 2013 (http://www.bjepb.gov.cn/).

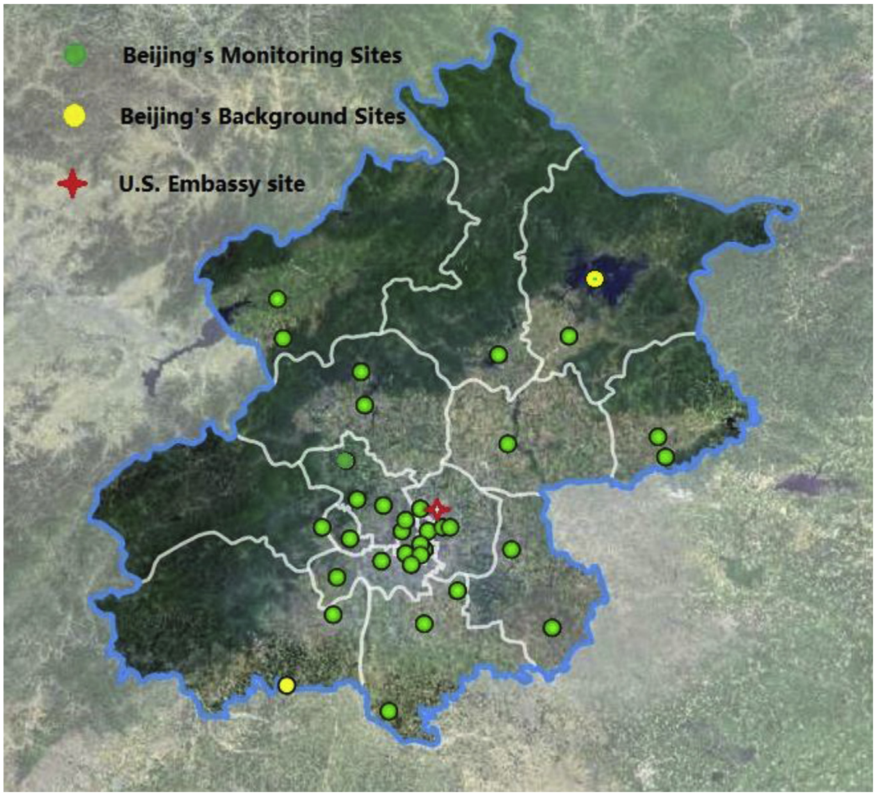

Fig. 4. Distribution of $PM_{2.5}$ monitoring sites in Beijing.

both values were far more than the China's AAQS Grade-II standard of 35 μg m^{-3}, which were over 2 times higher than the guideline value. Moreover, it can be concluded from Fig. 3 that in 2013, air pollution was mainly dominated by $PM_{2.5}$ pollution in Beijing.

3.1.4. Air quality improvement during the 2008 Beijing Olympic Games

In 2008, the 29th Summer Olympic Games was hosted in Beijing. Beijing's air quality had been significantly improved during the Games (8–24 August 2008) and 2–6 months after the Games, due to taking long-term control measures before the Games and short-term stringent control actions during the Games. Furthermore, it can be demonstrated from Fig. 3 that mass concentrations of major air pollutants (PM_{10}, SO_2 and NO_2) in Beijing showed a decreasing trend from before the Games to during the Games, reached the lowest levels 2–6 months after the Games, and increased afterwards except for PM_{10} and SO_2. Likewise, it was reported in the literature (Streets et al., 2007; Wang et al., 2010; Schleicher et al., 2012) that $PM_{2.5}$ mass concentrations during the Games were proved to the lowest levels due to stringent control actions before and during the games.

3.2. Current status of air pollution in Beijing

3.2.1. $PM_{2.5}$ pollution in Beijing (taking heavy haze pollution episodes in January 2013 for example)

In January 2013, China experienced several haze pollution episodes (Huang et al., 2014; Ji et al., 2014), which were the most serious particulate pollution events (excluding dust episodes) in the past two decades. Based on the statistical data from monitoring by Chinese Academy of Sciences (CAS), downtown Beijing's $PM_{2.5}$ level exceeded China's AAQS limit value of 75 μg m^{-3} (Grade II) for 22 days and exceeded China's AAQS limit value of 35 μg m^{-3} (Grade I) for 27 days (He et al., 2014). According to the World Health Organization (WHO) safety standard of 10 μg m^{-3}, downtown $PM_{2.5}$ exceeded the standard for nearly the whole month. In some extreme cases, daily average concentrations of $PM_{2.5}$ in Beijing exceeded the record range of monitoring instrument, which was also called by "record-breaking of $PM_{2.5}$". Among the heavy pollution episodes, two typical pollution processes were paid more attentions by both scientists and governments. One is a sharp growth in $PM_{2.5}$ concentrations within several hours (local time: 11:00–16:00, January 12, Fig. 5), which was mainly caused by local emissions and rapid formation of secondary $PM_{2.5}$. $PM_{2.5}$ precursors, such as SO_2, NO_2, NH_3 and VOCs etc., can be transformed to secondary $PM_{2.5}$ by homogeneous and/or heterogeneous atmospheric chemical reactions within just a few hours under stagnant weather conditions (Wang et al., 2013; Ji et al., 2014; Tao et al., 2014; He et al., 2014). It can be seen from Fig. 5 that, accompanied by high concentrations of $PM_{2.5}$, high concentrations of SO_2, NO_2, and NH_3 was also observed during the same period. Another is a continuous increase in $PM_{2.5}$ concentrations within several days (January 26–30), which was largely ascribed to regional transport and local accumulation. Therefore, it can be confirmed from the above two typical pollution processes that $PM_{2.5}$ pollution in Beijing mainly originated from local emission, secondary formation under special weather conditions, local accumulate, and regional transport.

3.2.2. Source apportionment of $PM_{2.5}$ in Beijing

On 16 April 2014, Beijing' EPB released the latest results of $PM_{2.5}$ source apportionment (http://www.bjepb.gov.cn/). Fig. 6 illustrated the results of $PM_{2.5}$ source apportionment in Beijing, local emission was the major contributor to Beijing's $PM_{2.5}$, while regional transport was minor contributor. Furthermore, it can be seen from Fig. 6 that local emission approximately contributed to

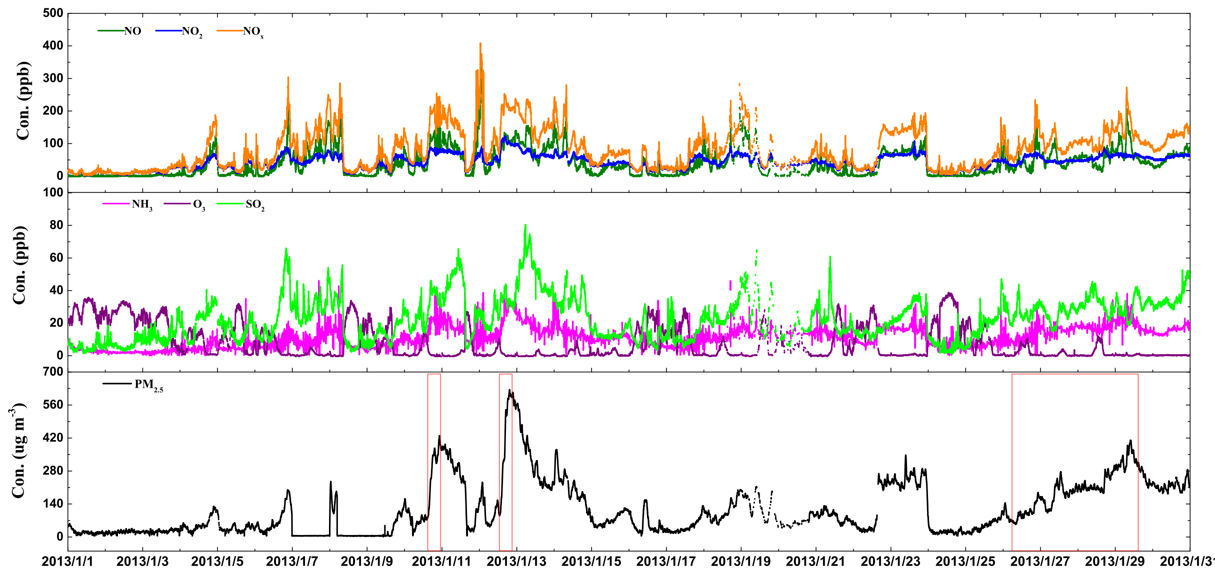

Fig. 5. Temporal patterns of NO, NO_2, NO_x, SO_2, NH_3, O_3, and $PM_{2.5}$ in January 2013.

64–72% of Beijing's $PM_{2.5}$, suggesting that $PM_{2.5}$ pollution in Beijing predominantly originated from local emissions. Among these local emission sources, the four major contributors to Beijing's $PM_{2.5}$ were motor vehicle (31.1%), coal combustion (22.4%), industrial production (18.1%), fugitive dusts (14.3%). The remaining emission sources of 14.1% were derived from cooking fume, vehicle maintenance and repair, livestock and poultry breeding, and building coatings and painting etc. The dominating chemical components of Beijing's $PM_{2.5}$ were organic matter (OM), nitrate, sulfate, crustal element, and ammonium, accounting for 26%, 17%, 16%, 12%, and 11%, respectively. In comparison, regional transport roughly accounted for 28–36% of Beijing's $PM_{2.5}$, which indicated that pollutant emissions from Beijing's neighboring municipalities, provinces, and autonomous regions, such as Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia, exerted significant effect on Beijing's air quality. Moreover, it was worth mentioning that

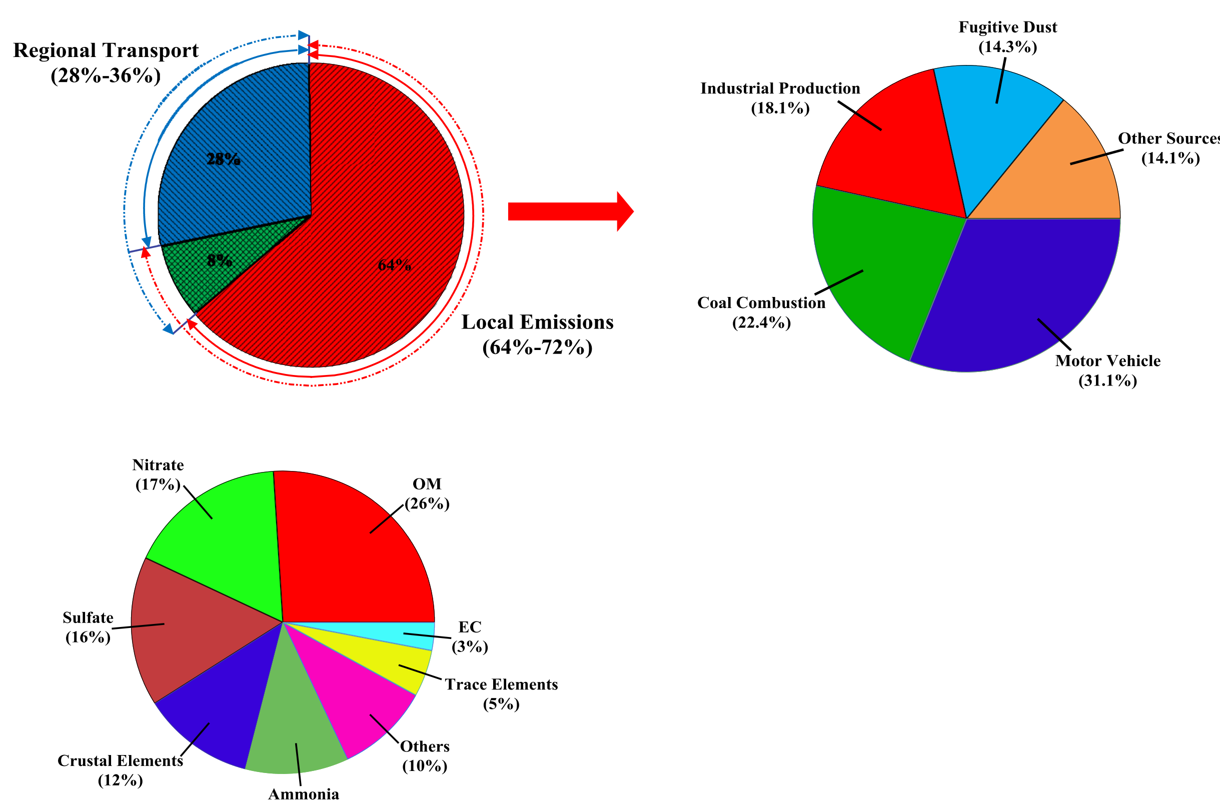

Fig. 6. Relative contribution of local emissions and regional transport, source allocation of $PM_{2.5}$, and chemical composition of $PM_{2.5}$ in Beijing.

according to the results of $PM_{2.5}$ source apportionment, vehicle emissions, as the most important contributor to local $PM_{2.5}$ pollution, could evidently lead to the deterioration of Beijing's air quality, which was needed to be addressed as the most important task.

4. Control action in Beijing

In response to Beijing's air pollution, control measures and action plans were formulated and implemented by Beijing's government based on national policies and regulations on air pollution prevention and control. In the following Sections 4.1 and 4.2, we briefly introduced control actions taken by Beijing's government in the past and at present.

4.1. Control actions before, during, and a short time after the Olympic Games

On 13 July 2001, Beijing was awarded to host the 29th Summer Olympic Games. Afterwards, the Beijing Organizing Committee for the Games promoted three concepts of "Green Olympics, High-tech Olympics and People's Olympics". "Green Olympics" aimed to highlight the importance of eco-environment protection. Therefore, in order to provide a blue sky for athletes and attendees, Beijing's government implemented a series of policy measures and took the corresponding control actions to ensure air quality improvement (Chen et al., 2013), such as converting 1500 coal furnaces into clean fuels, retiring 23,000 old automobiles, cutting major pollutant emissions of 30,000 tons, and increasing green coverage of 100 km^2. Between 2003 and 2004, Beijing reduced industrial coal consumption by 10,000 tons, required YanShan Petrochemical Company to install flue-gas desulfurization systems, shut down coal-fired power plant of both Capital Steel Company and Beijing Coking Plant, and closed Beijing Dyeing Plant. In the period of 2005–2006, Beijing constructed and installed desulfurization, dust removal, and denitrification facilities at both Beijing Thermal Power Plant and Capital Steel Power Plant. Furthermore, Capital Steel Company, the largest plant relocation project, started in 2005, finished the relocation of 73% of its production capacity during the Olympic Game, and completed all relocation by the end of 2010. Beijing Dyeing Plant, Beijing Coking Plant, and Second Beijing Chemical Plant completed its production closure in 2003, 2006, and 2007, respectively.

In order to reduce the impact of vehicle emissions on urban air quality before and during the Olympic Games, Beijing has adopted a number of vehicle emission control strategies and policies (Zhang et al., 2014). For instance, Beijing strengthened vehicle-emissions standards and restricted the number of on-road vehicles based on even-odd number of vehicle registration during the period of from August 17, 2007 to August 20, 2007 and from July 20, 2008 to September 20, 2008. From 1 July 2008 to 20 September 2008, about 300,000 heavily polluting vehicles (the so called yellow-label vehicles) were banned from Beijing's roads. Likewise, ~70% of government vehicles were ordered off the road during the same period. Moreover, some other control measures and actions about vehicle emissions, such as emission standard enhancement, fuel quality improvement, public transportation promotion, and alternative-fuel and advanced vehicles usage etc., were employed to reduce air pollution.

During the Olympic Games, Beijing's neighboring municipality, provinces, and autonomous regions, such as Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia, took similar control measures to improve ambient air quality, but the control magnitudes might be smaller than those for Beijing. For example, Tianjin and Hebei implemented the same odd-even traffic control and carried out road sweeping and washing to reduce fugitive dust during the Olympic Games. Shandong requested closure of 132 heavy polluting plants during the Games and installed desulfurization facilities for power-plant. Similarly, Shanxi and Inner Mongolia took concrete actions to control coal-fired pollution.

4.2. Control actions after haze pollution episodes happened in January 2013

4.2.1. 4.2.1Control actions in Beijing

To prevent and control air pollution, especially $PM_{2.5}$ pollution, Beijing's government has made tremendous efforts to improve air quality. Based on national policies and regulations on air pollution prevention and control, Beijing's government accordingly formulated "Clean Air Action Plan" and "Air Pollution Prevention and Control regulations". To ensure that by 2017, annual average concentrations of $PM_{2.5}$ should be controlled below 60 $\mu g\ m^{-3}$, Beijing's government promoted six engineering of air pollution prevention and control, such as (1) motor vehicle pollution control, (2) coal-fired pollution control, (3) key polluted industries control, (4) fugitive dust pollution control, (5) ecological restoration and recovery, and (6) new technology application in environmental protection.

The major task of control actions in Beijing is vehicle emission pollution control. To ensure that the total number of vehicles in Beijing will be restricted to around 6 million by the end of 2017, Beijing's government advocated the establishment of the 'green transportation' system and the implementation of 'public transportation priority' strategy and further took effective actions to guide the public, especially in urban areas, choosing public transport. The specific control actions included public transport development, vehicle population control (license-plate lottery), vehicle emission standard enhancement, vehicle emission inspection and maintenance (I/M) improvement, fuel quality improvements, retrofit or retirement of yellow-sticker and old vehicles, clean energy vehicle introduction, cost increasing of driving a car, vehicle management from other cities, etc.

To control coal-fired pollution, actions were taken to facilitate the construction of natural gas-fired combined heat and power (CHP) project, clean energy replacement of coal-fired boilers, and integrated prevention and control of low non-point source pollution. In response to key polluted industries pollution, measures were taken to accelerate the elimination of high-polluting industries and backward productivity, improve the advanced treatment of industrial pollution, and carry out the collection and subsequent treatment of cooking fume. In order to prevent urban fugitive dust, great effects were made to control fugitive dust at construction sites, seal sediment transport vehicles, promote low-dust automated road sweeping, and increase the green areas in the cities and suburbs. In addition, ecological restoration and recovery, such as increasing green coverage, new technology application in environmental protection, such as new clean energy vehicle, fuel quality improvement technology, denitrification and VOCs control technology, were also put forward.

4.2.2. Control actions in Beijing's neighboring areas (Beijing-Tianjin-Heibei region)

To effectively reduce Beijing's air pollution, the taken control measures and actions in Beijing-Tianjin-Hebei region and surrounding area are of essential importance to Beijing's air quality improvement. Therefore, China's MEP issued 'Action Plan on Prevention and Control of Air Pollution in Beijing-Tianjin-Hebei Region and Surrounding Area'. Based on 'Action Plan on Prevention and Control of Air Pollution in Beijing-Tianjin-Hebei Region and Surrounding Area', Beijing's surrounding municipalities, provinces, and autonomous regions, such as Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia, coordinated with each other and made the unifying arrangements and actions in emission source control, energy structure adjustment, industrial structure optimization, end-of-pipe treatment, urban meticulous management, eco-environment protection and emergency response of heavy air pollution. The detailed control actions in Beijing's neighboring areas included retirement of small coal-fired boiler, pollution control of key industries, pollution control of non-point source, management of urban transport, total population control of urban vehicles, improvement of fuel quality, retirement of yellow-sticker, enhancement of vehicle emission standards, introduction of new energy vehicle, strict industry and environment access threshold, elimination of backward productivity, total amount control of coal consumption, clean energy supply, clean usage of coal, etc.. These control actions taken by Beijing's neighboring areas have a substantial impact on improvement of Beijing's air quality. For instance, during the APEC week in 2014, blue skies (also called 'APEC blue') appeared in Beijing, which was a result of tough emission-reduction measures in Beijing-Tianjin-Hebei Region and Surrounding Area.

5. Conclusions

In this paper, firstly, we introduced national ambient air quality standards, national policies and regulations on air pollution prevention and control, including '*Joint Prevention and Control of Air Pollution*', '*Action Plan of Prevention and Control of Air Pollution*', and '*Action Plan of Prevention and Control of Air Pollution in Beijing - Tianjin - Hebei region and Surrounding Area*'. Afterwards, we presented the historical evolution of major air pollutants (PM_{10}, SO_2 and NO_2) from 1998 through 2013, analysed current status of Beijing's air pollution (taking heavy haze pollution episodes in January 2013 for example), and interpreted the results of Beijing's $PM_{2.5}$ source apportionment. Finally, we reported control measures and actions taken in both Beijing and its neighboring areas.

This study can provide the basic information about China's urban air pollution for scientists and governments in the world, which help have a good knowledge about the current status of urban air pollution in China and assess the effectiveness of control measures and actions taken by Chinese government. In view of China's urban air pollution complex and the resulting control measures and actions under China's specific national conditions, it would be expected to provide some valuable references to the other countries when facing a variety of urban air pollution problems.

Acknowledgements

The present work is supported by Beijing Municipal Science and Technology Project (No. Z141106001014018), Opening Project of Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP^3), Opening Project of State Key Laboratory of Organic Geochemistry, and Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry. In addition, we would like to express our sincere gratitude to other participants for their invaluable assistance.

References

Brunekreef, B., Holgate, S., 2002. Air pollution and health. Lancet 360, 1233–1242.
Chan, C., Yao, X., 2008. Air pollution in mega cities in China. Atmos. Environ. 42, 1–42.
Chen, Y., Jin, G., Kumar, N., Shi, G., 2013. The promise of Beijing: Evaluating the impact of the 2008 Olympic Games on air quality. J. Environ. Econ. Manag. 66, 424–443.
Chinese National Bureau of Statistics, 2013. http://www.stats.gov.cn/english/statisticaldata/AnnualData/.
Dominici, F., Greenstone, M., Sunstein, C., 2014. Particulate matter matters. Science 344, 257–259.
Han, L., Zhou, W., Li, W., Li, L., 2014. Impact of urbanization level on urban air quality: A case of fine particles ($PM_{2.5}$) in Chinese cities. Environmental Pollution 194, 163–170.
He, H., Wang, Y., Ma, Q., Ma, J., Chu, B., Ji, D., Tang, G., Liu, C., Zhang, H., Hao, J., 2014. Mineral dust and NOx promote the conversion of SO2 to sulfate in heavy pollution days. Sci. Reports 4 (4172), 1–5.
Hu, J., Wang, Y., Ying, Q., Zhang, H., 2014. Spatial and temporal variability of $PM_{2.5}$ and PM_{10} over the North China Plain and the Yangtze River Delta, China. Atmos. Environ. 95, 598–609.
Huang, R., Zhang, Y., Bozzetti, C., Ho, K., etc, 2014. High secondary aerosol contribution to particulate pollution during haze events in China. Nature 524 (7521), 218–222.
Ji, D., Li, L., Wang, Y., Zhang, J., Cheng, M., Sun, Y., Liu, Z., Wang, L., Tang, G., Hu, B., Chao, N., Wen, T., Miao, H., 2014. The heaviest particulate air-pollution episodes occurred in northern China in January, 2013: Insights gained from observation. Atmos. Environ. 92, 546–556.
Kan, H., Chen, R., Tong, S., 2012. Ambient air pollution, climate change, and population health in China. Environ. Int. 42, 10–19.
Li, W., Shao, L., Shi, Z., Chen, J., Yang, L., Yuan, Q., Yan, C., Zhang, X., Wang, Y., Sun, J., Zhang, Y., Shen, X., Wang, Z., Wang, W., 2014. Mixing state and hygroscopicity of dust and haze particles before leaving Asian Continent. J. Geophys. Res. Atmos. 119, 1044–1059.
Li, W., Zhou, S., Wang, X., Xu, Z., Yuan, C., Yu, Y., Zhang, Q., Wang, W., 2011. Integrated evaluation of aerosols from regional brown hazes over Northern China in winter: concentrations, sources, transformation, and mixing states. J. Geophys. Res. Atmos. 116, D09301.
Nel, A., 2005. Air pollution-related illness effects of particles. Science 308, 804–806.
Parrish, D., Zhu, T., 2009. Clean air for megacities. Science 326, 674–675.
Schleicher, N., Norra, S., Chen, Y., Chai, F., Wang, S., 2012. Efficiency of mitigation measures to reduce particulate air pollution—A case study during the Olympic Summer Games 2008 in Beijing, China. Sci. Total Environ. 427–428, 146–158.
Shao, M., Tang, X., Zhang, Y., Li, W., 2006. City clusters in China: air and surface water pollution. Front. Ecol. Environ. 4 (7), 353–361.
Streets, D., Fu, J., Jang, C., Hao, J., He, K., Tang, X., Zhang, Y., Wang, Z., Li, Z., Zhang, Q., Wang, L., Wang, B., Yu, C., 2007. Air quality during the 2008 Beijing Olympic Games. Atmos. Environ. 41, 480–492.
Tao, M., Chen, L., Xiong, X., Zhang, M., Ma, P., Tao, J., Wang, Z., 2014. Formation process of the widespread extreme haze pollution over northern China in January 2013: Implications for regional air quality and climate. Atmos. Environ. 98, 417–425.
Wang, J., Wang, Y., Liu, H., Yang, Y., Zhang, X., Li, Y., Zhang, Y., Deng, G., 2013. Diagnostic identification of the impact of meteorological conditions on $PM_{2.5}$ concentrations in Beijing. Atmos. Environ. 81, 158–165.
Wang, S., Hao, J., 2012. Air quality management in China: issues, challenges, and options. J. Environ. Sci. 24 (1), 2–13.
Wang, S., Xing, J., Zhao, B., Jang, C., Hao, J., 2014. Effectiveness of national air pollution control policies on the air quality in metropolitan areas of China. J. Environ. Sci. 26, 13–22.
Wang, T., Nie, W., Gao, J., Xue, L., Gao, X., Wang, X., Qiu, J., Poon, C., Meinardi, S., Blake, D., Wang, S., Ding, A., Chai, F., Zhang, Q., Wang, W., 2010. Air quality during the 2008 Beijing Olympics: secondary pollutants and regional impact. Atmos. Chem. Phys. 10, 7603–7615.
Wu, Y., Wang, R., Zhou, Y., Lin, B., Fu, L., He, K., Hao, J., 2011. On-road vehicle emission control in Beijing: past, present, and future. Environ. Sci. Technol. 45 (1), 147–153.
Zhang, J., Ouyang, Z., Miao, H., Wang, X., 2011. Ambient air quality trends and driving factor analysis in Beijing, 1983–2007. J. Environ. Sci. 23 (12), 2019–2028.
Zhang, Q., He, K., Huo, H., 2012. Cleaning China's air. Nature 484, 161–162.
Zhang, S., Wu, Y., Wu, X., Li, M., Ge, Y., Liang, B., Xu, Y., Zhou, Y., Liu, H., Fu, L., Hao, J., 2014. Historic and future trends of vehicle emissions in Beijing, 1998-2020: a policy assessment for the most stringent vehicle emission control program in China. Atmos. Environ. 89, 216–229.
Zhao, B., Xu, J., Hao, J., 2011. Impact of energy structure adjustment on air quality: a case study in Beijing, China. Front. Environ. Sci. Eng. China 5 (3), 378–390.
Zhao, Y., Wang, S., Wang, J., Fu, J., Liu, T., Xu, J., Fu, X., Hao, J., 2013. Impact of national NOx and SO2 control policies on particulate matter pollution in China. Atmos. Environ. 77, 453–463.