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Research article

Monitoring history and change trends of ambient air quality in China during the past four decades

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ABSTRACT

This study summarized the history of ambient air quality monitoring and air pollution prevention and control, and it analyzed the spatiotemporal patterns of ambient air pollutants during 1981–2017 in China. The results showed that monitoring of ambient air quality has changed dramatically in terms of determinants, sampling methods, monitoring extent, and evaluation basis during the previous four decades. Annual average concentrations of total suspended particulates, PM_{10} and SO_2 have shown obvious decreasing trends during the studied period. These improvements have been closely related to the considerable efforts and various approaches undertaken to prevent and control air pollution. However, although policy implementation has been decisive and, at least in part, it has been enforced effectively, significant challenges remain. Air pollution control cannot be accomplished without a long-term strategy designed to achieve clean air in all parts of China.

1. Introduction

In the decades since the start of the Reform and Opening-up in 1978, China has experienced rapid industrialization, urbanization, and motorization (Chan and Yao, 2008; Kan et al., 2012; Rohde and Muller, 2015). Consequently, air pollution has become an increasingly severe environmental issue because of the marked growth in energy consumption and the resulting multiple pollutant emissions (Chan and Yao, 2008; Rohde and Muller, 2015). However, in response to the increasing hazard posed by air pollution, the Chinese government has both implemented a series of policies, measures and regulations designed to prevent and control air pollution and adopted certain concrete actions to improve regional air quality (Jin et al., 2016; Wang et al., 2018; Zhang et al., 2011b, 2016b, 2017).

Considerable attention has been given to urban ambient air quality, especially regarding the negative effects of urban air pollution on human health, climate change, and visibility (Huang et al., 2018; Liu et al., 2018; Maji et al., 2018; Zhang et al., 2015). The air quality trend is of primary concern, and recent research has indicated that worldwide trends in ambient air quality typically show reductions in the concentration of certain pollutants, e.g., SO_2 and NO_2 (MEP, 2017, 2018; Zhang et al., 2011b). With growing public awareness of the detrimental effects of air pollution, numerous empirical studies have focused overwhelmingly on the spatiotemporal variations of air pollution, which are vital for evaluation of the health risks associated with human exposure (Kan et al., 2012; Zhang et al., 2011a, 2016a). Previous studies have examined the spatial characteristics of air pollution on scales ranging from the local to the regional scale (Chan and Yao, 2008; Chen et al., 2017; Hu et al., 2014; Liu et al., 2018; Ma et al., 2014; Wang and Fang, 2016; Yang et al., 2018; Zhao et al., 2018b). However, most of studies on ambient air quality conducted in China have focused largely on reasonably small areas or regions (Zhan et al., 2017; Zhang et al., 2011b), e.g., major metropolitan cities such as Beijing (Chen et al., 2015; Zhai et al., 2018), Shanghai (Liu et al., 2016; Wang et al., 2015), and Guangzhou (Chan and Yao, 2008; Wang et al., 2016) and on urban agglomerations such as Jing-Jin-Ji (Chen et al., 2017), the Bohai Rim (Wang and Fang, 2016), and the Yangtze River Delta (Hu et al., 2014). The lack of comprehensive air quality data has meant that systematic

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nationwide research on the history of air quality monitoring is lacking, and that the spatiotemporal variations of air pollution in China on the national scale, based on ground monitoring data, are not fully understood (Engel-Cox et al., 2013; Zhan et al., 2017). Although the Chinese government does release national reports on quarterly/annual environmental quality or five-year environmental quality (MEP, 2017, 2018; MEE, 2018, 2019a, 2019b, 2019c), reports and studies on the long-term trends of environmental air quality are rare.

The year 2018 marked the 40th anniversary of the Reform and Opening-up in China. Improved understanding and systematic study of the history of the monitoring of ambient air quality, as well as investigation of the temporal changes and spatial distribution patterns of air pollutants, and the measures adopted for control and prevention of air pollution in China, are essential for the formation of effective management strategies regarding urban air pollution control. This study summarized the history of air quality monitoring in China in terms of the determinants monitoring extent, monitoring methods, ambient air quality standards, and requirements regarding data validation. Moreover, the history of the control and prevention of air pollution in China was established and the spatiotemporal patterns of air pollutants since the 1980s were analyzed. The results of this study provide an environmental monitoring history and constitute reliable information on the spatiotemporal patterns of air quality in China that could represent a useful resource for the public and ongoing scientific research.

2. Methodology

2.1. Study area

With consideration of the availability and integrity of both monitoring history data and air quality data, the study area for this research comprised mainland China, including all 338 cities at or above prefecture level (including municipalities, cities, or regions at prefecture level, autonomous prefectures, and leagues; hereafter, referred to as the 338 cities). However, Hong Kong, Macao, and Taiwan were excluded from the study because of the lack of complete data sets.

2.2. Data sources

Monitoring history and levels of air pollutants were derived from annual reports on environmental quality in China (1981–2018) (MEP, 2018; MEE, 2019a, 2019b, 2019c), reports on the state of the environment in China (1986–2018) (MEE, 2018; MEP, 2017), annual reports on the work of the Chinese government, and the China National Environmental Monitoring Network, developed by the China National Environmental Monitoring Center (CNEMC). The CNEMC is a public institution directly affiliated to Ministry of Ecology and Environment of China (MEE), it plays an important role as the center of technology, networks, information, quality control, and training for national environmental monitoring. It collects at least 100 million environmental monitoring data annually, which support the scientific and accurate assessment of the national environmental quality.

2.3. Method

The spatial distributions of ambient air quality monitoring sites and air pollutants were presented using ArcGIS 10.2, and the temporal patterns of air pollutants were summarized using Origin 2018.

3. Monitoring history on ambient air quality in China

In China, monitoring of environmental quality began in the early 1970s, and increasing numbers of provincial- and city-level environmental monitoring stations were established over subsequent years as a reflection of China's economic and technological development (Fig. 1). Currently, China has a four-tiered environmental monitoring system that comprises national-, provincial-, municipal-, and county-level environmental monitoring stations. Over past years, large amounts of environmental quality monitoring data have been accumulated by environmental quality monitoring departments at different levels. The CNEMC is the national level, it has an important role as the center of technology, networks, information, quality control, and training in relation to national environmental quality monitoring. It collects at least 100 million environmental monitoring data annually that are used to support the scientific and accurate assessment of national environmental quality.

During the previous four decades in China, rapid socioeconomic development, technological advances, and changes in the status of particulate matter (PM) pollution have meant that the monitoring of ambient air quality has changed dramatically in terms of the monitored items, methods and scope of monitoring, and basis for evaluation. In 1989, the CNEMC formulated the "National Environmental Monitoring Network Management Regulations" (draft). After optimization of the design, 74 national control stations were identified for atmospheric environmental monitoring. The main items monitored were total suspended particulates (TSPs), SO_2, and NO_X. At that time, manual sampling was the dominant measurement method. During the period of the 9th and 10th Five-Year Plan, an automatic ambient air monitoring system was developed rapidly and integrated into China's National Environmental Monitoring Network. During the period of the 11th Five-Year Plan, the National Ambient Air Quality Monitoring Network included 661 monitoring sites, covering 113 key environmental protection cities, with PM with aerodynamic diameter of $\leq$10 μm (PM_{10}), SO_2, and NO_2 as the main monitoring items. By this time, automatic monitoring methods had been adopted at all monitoring sites; thus, achieving continuous automatic monitoring 24 h per day. At the beginning of 2012, having been adopted by the State Council executive meeting, the government promulgated and implemented the environmental Ambient Air Quality Standard (GB 3095-2012). In April of the same year, the Ministry of Environmental Protection (MEP) approved a new plan for extending the National Ambient Air Quality Monitoring Network. The objective of this plan was to expand the monitoring scope in China to all 338 cities at or above prefectural level, and to increase the number of monitoring sites from 661 to 1436, achieving full coverage of the national monitoring network.

The former Ministry of Environmental Protection of China (MEP) introduced a three-step program to implement the new Ambient Air Quality Standard for urban air quality monitoring. In the first step, 74 pioneer cities commenced monitoring following the new standards from 2012. These cities comprised the municipalities directly under the central government, provincial capitals, cities with separate plans, and

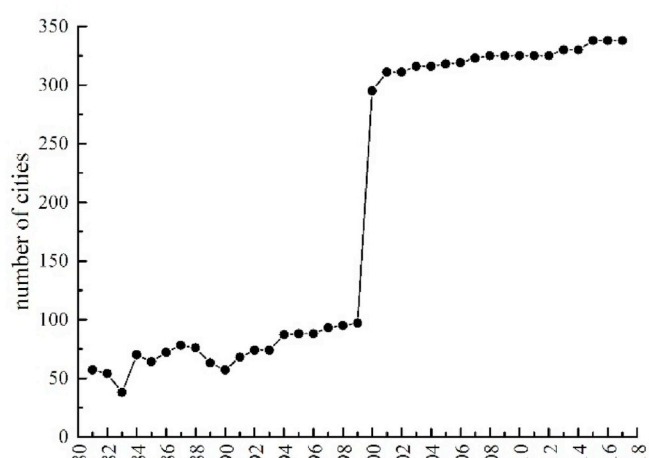

Fig. 1. Number of cities conducting air quality monitoring in China.

the Beijing–Tianjin–Hebei (BTH), Pearl River Delta (PRD), and Yangtze River Delta (YRD) regions. In the second step, in 2013, a further 169 cities that comprised national key environmental protection cities and environmental protection model cities adopted the new standards for air quality monitoring. The third step required that all 338 cities in China at or above prefectural level should conduct air quality monitoring following the new standards from January 1, 2015.

According to the requirements of the Air Pollution Prevention and Control Action Plan, which was released by the State Council on September 10, 2013, all cities at or above prefectural level were required to construct sites for the monitoring of fine PM (aerodynamic diameter: ≤2.5 μm; $PM_{2.5}$), these sites are administered directly by the State. The CNEMC completed the work on the network for the collection of national ambient air quality data. Consequently, all 1436 urban air quality monitoring sites in China are under unified management of the CNEMC, and they are operated specifically by social operation and maintenance

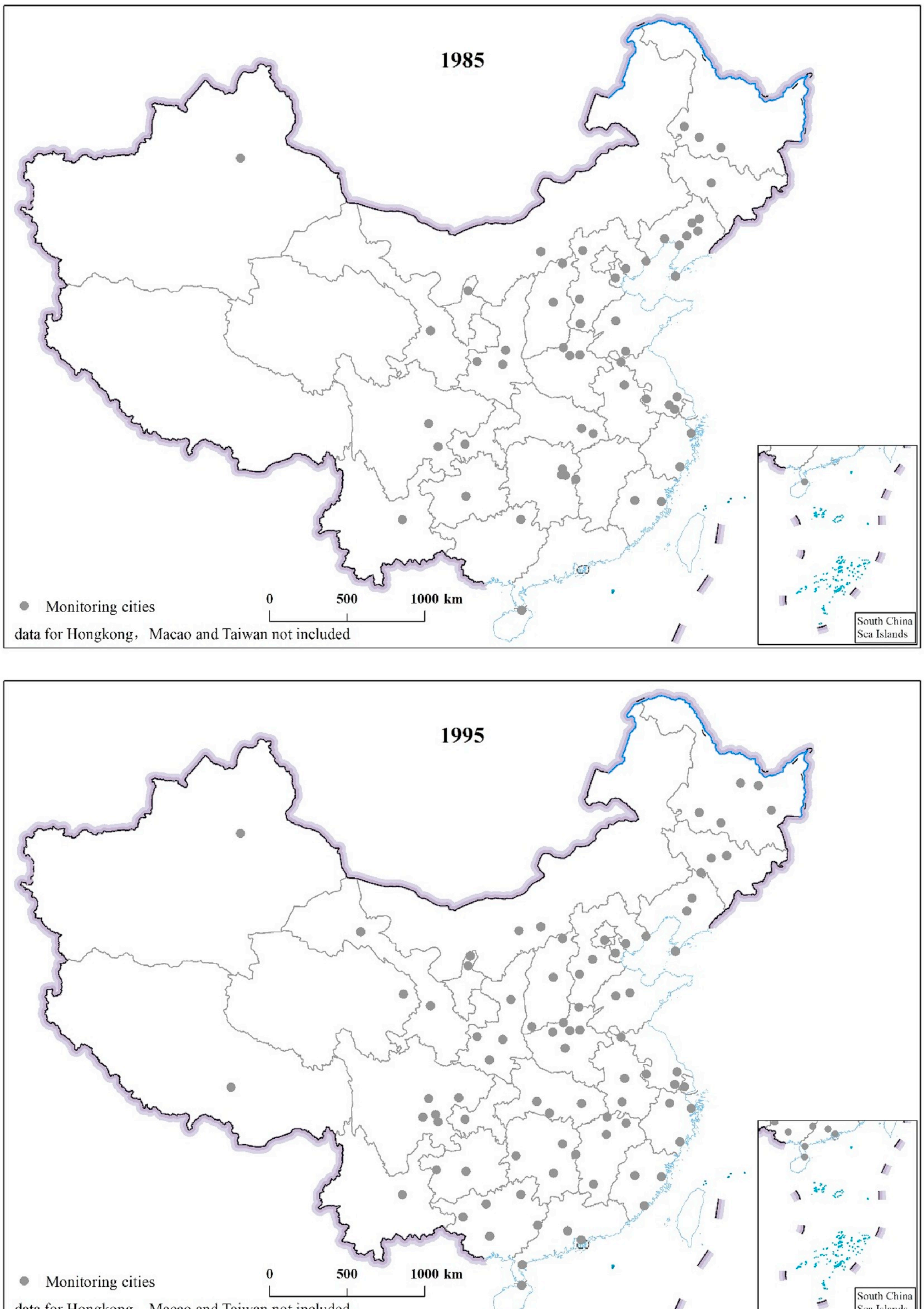

Fig. 2. Spatial distribution of cities in China conducting air quality monitoring in 1985, 1995, 2005, and 2015.

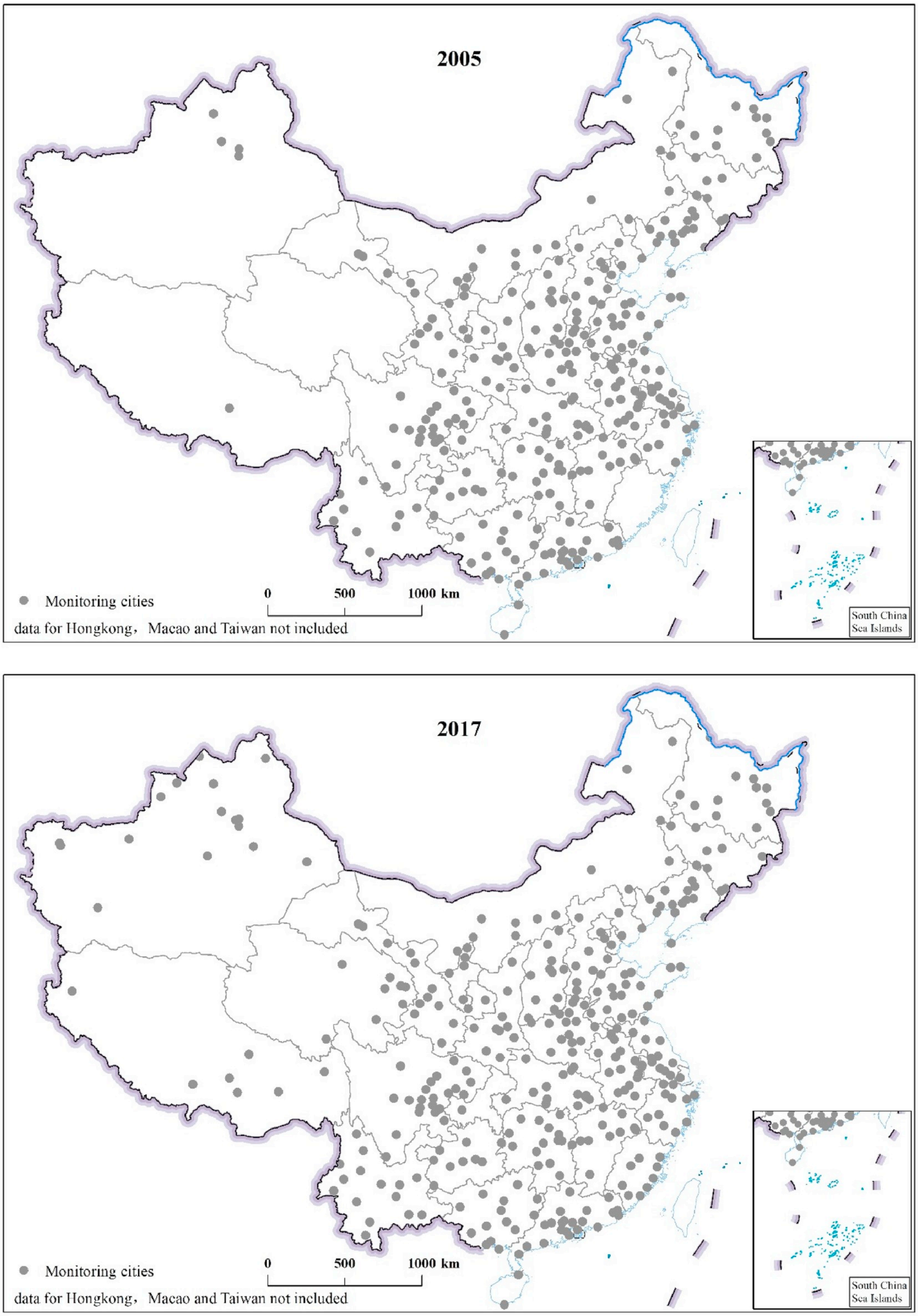

Fig. 2. (*continued*).

institutions. Through this arrangement, the roles of the central and local authorities have been clarified and the "national assessment, national monitoring" program has been achieved. This organizational structure has had an important effect on both resolving administrative interventions and alleviating the pressure and burden on grassroots units.

3.1. Air quality monitoring network

After 40 years' development, China has established both national and local environmental air quality monitoring networks with well-defined functions (Fig. 2). The National Ambient Air Monitoring Network mainly includes the National Urban Environmental Air Quality Monitoring Network, National Regional Environmental Air Quality Monitoring Network, and National Ambient Air Background Monitoring

Network, etc. (see details in Appendix Table 1). The local environmental air monitoring network is a further extension of the national network, covering the county level, although some provinces even cover the township level. The national ambient air quality monitoring network in China is the largest air quality monitoring network in the developing countries.

The National Urban Ambient Air Quality Monitoring Network is the principal body of China's ambient air quality monitoring network; it is also China's earliest air monitoring network. It is used mainly to monitor the ambient air quality of built-up urban areas or different functional areas, to evaluate the overall air quality status and air quality compliance in built-up urban areas, to reflect exposure to pollutants in densely populated areas, and to provide technical support for environmental management and public information services. In the mid-1970s, cities such as Beijing and Shenyang commenced urban ambient air quality monitoring, and the earliest form of the National Urban Air Quality Monitoring Network was established in the 1980s. In 1992, the National Urban Air Quality Monitoring Network comprised 103 city-level monitoring centers. Even up until the end of 2010, the network consisted of only 113 key environmental protection cities. In 2012, the adjustment work of the National Urban Ambient Air Quality Monitoring Network was completed and the monitoring scope of the network was expanded from the 113 original environmental protection key cities to 338 cities of prefecture-level or above in 31 provinces. The number of monitoring sites was adjusted from 661 to 1436, i.e., an increase of 775. At the same time, provinces, autonomous regions, and municipalities directly under the central government established more than 4000 provincial and municipal control points. Thus, China has built the largest urban environmental air quality monitoring network of any developing country.

3.2. Determinants

Monitoring of ambient air quality in China has followed a path of gradual transition from less to more and from coarse particles to fine PM. From the mid-1970s to 1999, the principal monitoring items for urban ambient air quality were SO_2, NO_X, dust, and TSP.

Cities such as Beijing, Hebei, Sichuan and some provinces took the lead in routine monitoring of inhalable particles (PM_{10}). Since June 5, 2000, 47 key environmental protection cities have undertaken routine monitoring of PM_{10}, and this has gradually been promoted across the entire country. In the meantime, the monitoring and assessment index of nitrogen oxides changed from NO_X to NO_2. By 2005, PM_{10} monitoring was implemented in all Chinese cities at or above prefectural level and monitoring of TSP stopped.

In 2006, Beijing initiated a pilot program for monitoring $PM_{2.5}$ and O_3. In 2008, cities such as Tianjin, Shanghai, and Chongqing adopted the same program for monitoring of $PM_{2.5}$ and O_3 and the number of pilot cities gradually increased to nine. By the end of 2012, 74 pioneer cities were routinely monitoring six air pollutants (PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, and CO), and since the beginning of 2015, 338 cities at or above prefectural level have been performing routine monitoring of the above six air pollutants.

3.3. Monitoring extent

The extent of monitoring ambient air quality has expanded gradually in China (Fig. 2). In the mid-1970s, only a few cities such as Beijing and Shenyang monitored air quality. In the mid-1980s, the number of cities conducting air quality monitoring was 60. By the mid-1990s, the number of cities performing monitoring of air pollutants was around 90; however, this number surged to 295 in 2000. In 2008, all cities at or above prefectural level conducted regular air quality monitoring, except for the provinces of Tibet and Qinghai, in which monitoring of air quality was performed only in the provincial capitals. By 2013, 5 cities in Qinghai Province had started regular air quality monitoring, and the number of cities at or above prefectural level involved in the monitoring of air pollutants was 330. By 2015, all cities in the provinces of Tibet, Qinghai, and Xinjiang were conducting routine air quality monitoring, and the total number of cities at or above prefectural level that were involved in the monitoring of air pollutants was 338.

3.4. Monitoring method

Monitoring of air pollutants in China has evolved from a manual process into comprehensive automatic monitoring. In the early period of air pollutant monitoring, a manual monitoring method called the Five-day Instantaneous Sampling Method was used. In this method, sampling and monitoring were conducted on five days per quarter, and during the five days, continuous sampling was performed for 30–60 min in the morning, at noon, and in the evening.

The introduction of the Ambient Air Quality Standard (GB 3095-1996) in 1996 improved the requirements concerning data validity. Consequently, the Five-day Instantaneous Sampling Method was replaced by 24-h continuous laboratory analysis. This required analysis of 24-h continuous sampling, daily average concentrations on 60 days distributed uniformly throughout the year, and daily average concentrations on 5 days distributed evenly in each month.

Some cities in China have used automatic monitoring since 1998. However, following a period of rapid progress, all key environmental protection cities had implemented automatic monitoring of PM by 2004. Thus, China had entered into the stage of construction of a comprehensive system for automatic monitoring for urban ambient air quality. In 2000, 47 key environmental protection cities began issuing regular air quality forecasts. Nowadays, daily ambient air quality reports, real-time air quality reports, and forecasts of ambient air quality are produced routinely.

3.5. Ambient air quality standard

Since the implementation of the first standards for ambient air quality in 1982, the standards have played an important role in both environmental protection and environment management. Following China's rapid socioeconomic development, the characteristics of ambient air pollution changed tremendously. Therefore, it has been necessary to revise the standards based on experience. During the previous three decades, there have been three major revisions of the standards for ambient air quality concerning PM and other air pollutants in China (see details in Appendix Table 2).

The first environmental Ambient Air Quality Standard (GB 3095-1982) was promulgated in 1982. It included the first set criteria for the evaluation of TSP, which specified a daily concentration of 0.3 mg/m^3 for Grade II standard of TSP. In 1996, the original standard was replaced by Ambient Air Quality Standard GB 3095-1996, which added criteria for the evaluation of daily (0.15 mg/m^3) and annual (0.10 mg/m^3) concentrations of PM_{10} for Grade II standard. In addition, an annual assessment standard for TSP was also added, which set an annual concentration of 0.20 mg/m^3 for Grade II standard. In 2012, the Chinese government released a new Ambient Air Quality Standard (GB 3095-2012), which was formulated in a bid to implement the Environmental Protection Law of the People's Republic of China and the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution. These laws were intended to protect and improve the living environment and the ecological environment as well as to safeguard human health. The new standards were the first to prescribe limits for $PM_{2.5}$ and they revised the evaluation criteria for PM_{10}. These new standards were comparable with the interim target (IT) set by the World Health Organization (WHO). Specifically, the Grade II standards for $PM_{2.5}$ and PM_{10} were set the same as WHO IT-1, i.e., daily and annual concentrations of 75 and 35 μg/m^3, respectively, for $PM_{2.5}$, and an annual concentration of 70 μg/m^3 for PM_{10}.

3.6. Requirements on data validation

Before 1996, monitoring of atmospheric PM was required on at least 5 (20) days per season (year). After 1996, in accordance with Ambient Air Quality Standard GB 3095-1996, monitoring of daily average pollutant concentrations on at least 60 days distributed uniformly throughout a year was required to derive annual daily concentration data. Furthermore, monitoring of daily pollutant concentrations on at least five days distributed evenly throughout a month was required to obtain monthly daily concentration data. Observations of pollutant concentrations over a 12-h period were required to derive daily average concentration data to ensure the representativeness of the daily average concentrations.

According to the Ambient Air Quality Standard GB 3095-2012 released in 2012, daily concentration data from at least 324 days were needed to obtain annual daily concentration data; daily concentration data from at least 27 days (no less than 25 days for February) were necessary to obtain monthly daily concentration data, and observations of pollutant concentrations from at least 20 h were required to derive daily average concentration data. These requirements were specified to ensure the representativeness of the daily average values of each monitoring site; otherwise, the annual/monthly/daily concentration data were considered invalid.

4. Results

4.1. TSP, dust, and PM_{10}

From the 1980s to the end of 20th century, the prevention of coal dust pollution was the focus of air pollution prevention and control in China. Monitoring data indicated that both the annual concentration of TSP (Fig. 3) and the annual amount of dust showed trends of decrease during this time (Fig. 4). From 1981 to 2000, the annual average concentration of TSP decreased from 0.702 to 0.258 mg/m^3 (a decrease of 63.2%) and the annual amount of dust fell from 33.97 to 14.21 t/km^2 (a decline of 58.2%).

During the first decade of the 21st century, following the implementation of new regulations and standards, the focus of national prevention and control of atmospheric PM pollution changed from TSP to PM_{10}. Air quality monitoring results showed that the overall annual average concentration of PM_{10} presented a downward trend during this period. From 2000 to 2017, the annual average concentration of PM_{10} showed a continued trend of decrease from 113 to 71 μg/m^3 (a decline of 37.2%).

Certain cities at or above prefectural level did not conduct PM_{10} monitoring during 2001–2004. Therefore, our analysis of the spatial

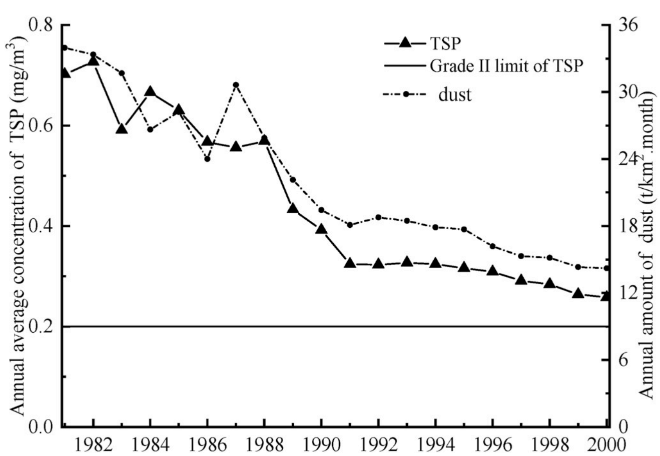

Fig. 3. Temporal trends of concentration of TSP and of annual amount of dust in China during 1981–2000.

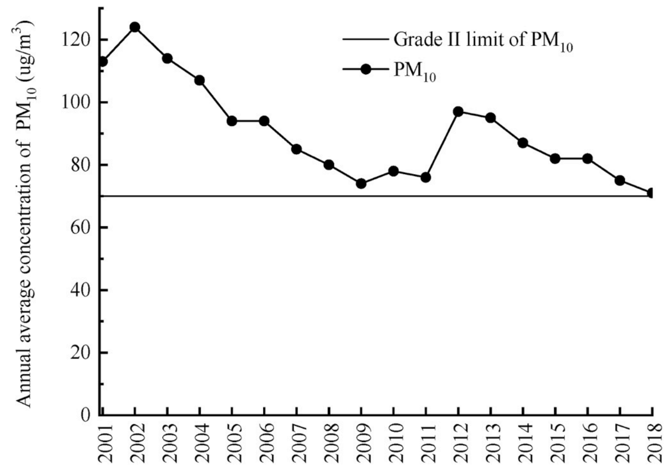

Fig. 4. Temporal trend of PM_{10} concentration in China during 2000–2018.

distribution of PM_{10} concentration focused on 2005, 2010, 2015, and 2017 (Fig. 5). The results showed evident mitigation of PM_{10} pollution between 2005 and 2017, with a significant decrease in heavily polluted areas and an increase in the overall area that met the Grade II national Ambient Air Quality Standard (GB 3095-2012). Annual average levels of PM_{10} concentration showed marked decrease in North China, Northeast China, Southwest China, and southern Central China. However, because of the effect of sand- and dust-related weather factors, PM_{10} pollution in Xinjiang remained prominent.

4.2. $PM_{2.5}$

Since 2013, air quality in China has improved considerably, with an obvious trend of decrease in the level of $PM_{2.5}$ both in key regions and in the entire country. The number of cities failing to meet the national Ambient Air Quality Standard has decreased annually (Table 1). In 2018, the annual average $PM_{2.5}$ concentration in the entire country was 9–74 μg/m^3 (average: 39 μg/m^3), i.e., down by 3.0% in comparison with 2017.

During 2013–2018, the annual average $PM_{2.5}$ concentration in cities under stage I monitoring based on the newly amended Ambient Air Quality Standard decreased from 72 to 42 μg/m^3 (a decrease of 41.7%). The annual average $PM_{2.5}$ concentration in the BTH area decreased from 106 to 55 μg/m^3 (a decrease of 48.1%), the annual average $PM_{2.5}$ concentration in the YRD area decreased from 67 to 41 μg/m^3 (a decrease of 38.8%), and the annual average $PM_{2.5}$ concentration in the PRD area decreased from 47 to 32 μg/m^3 (a decrease of 31.9%). The greatest improvement in terms of $PM_{2.5}$ pollution was achieved in the BTH area, and the total number of days under heavy or severe pollution in the three regions decreased from 721 to 184.

The stringent policies for air pollution control have mitigated daily $PM_{2.5}$ pollution markedly in key regions, e.g., the air quality in the BTH area meets the targets of the Air Pollution Prevention and Control Action Plan. The daily trends of $PM_{2.5}$ pollution in all cities of the BTH, YRD, and PRD regions from January 2013 to December 2017 are shown in Fig. 6. During 2013–2017, air quality improved greatly in these three key regions, with an obvious trend of decrease in daily $PM_{2.5}$ concentration and a reduction in the number of polluted days.

4.3. NO_X and NO_2

During 1981–2000, the annual average concentration of NO_X in China remained reasonably constant at about 45 μg/m^3 ±10% (Fig. 7). During 2001–2018, the annual average NO_2 concentration initially decreased up until 2008 but then subsequently increased slightly; however, the annual average NO_2 concentration met the Grade II limit of

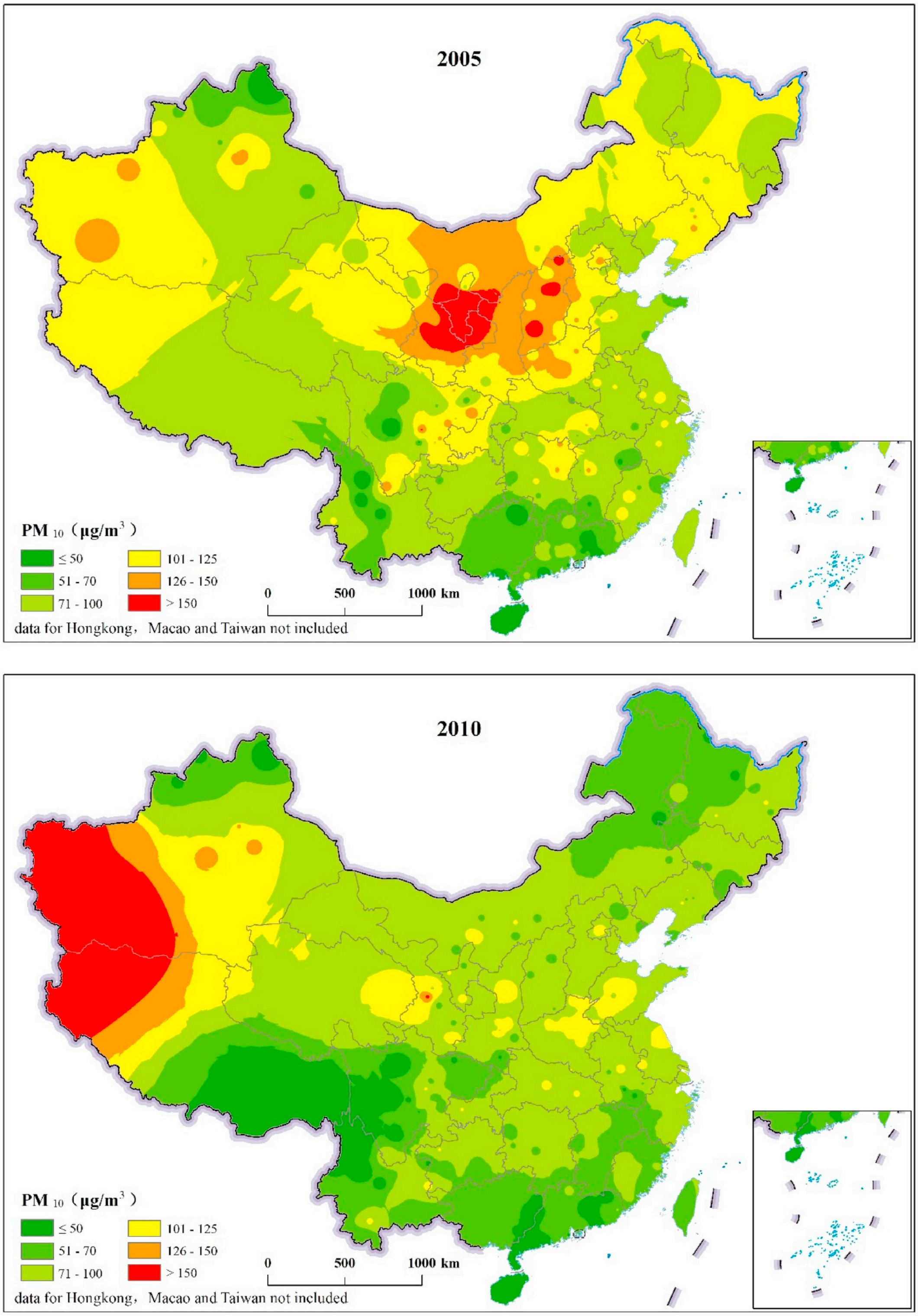

Fig. 5. Spatial distribution of PM_{10} concentration in China in 2005, 2010, 2015, and 2017.

the national Ambient Air Quality Standard (GB 3095-1996) throughout this period.

4.4. SO_2 and acid rain

From 1981 to 2018, the annual average concentration of SO_2 showed an obvious and continuous trend of decrease from 117 to 14 μg/m^3 (Fig. 8).

By 2017, in comparison with 2001, the acid rain pollution situation had been mitigated considerably and the area affected by acid rain had decreased markedly to about 620,000 km^2 (6.4% of the total land area of China), down by 8.5% compared with 2001. The provinces affected most by acid rain are distributed mainly in the region south of the Yangtze River and east of the Yunnan–Guizhou Plateau. These most of

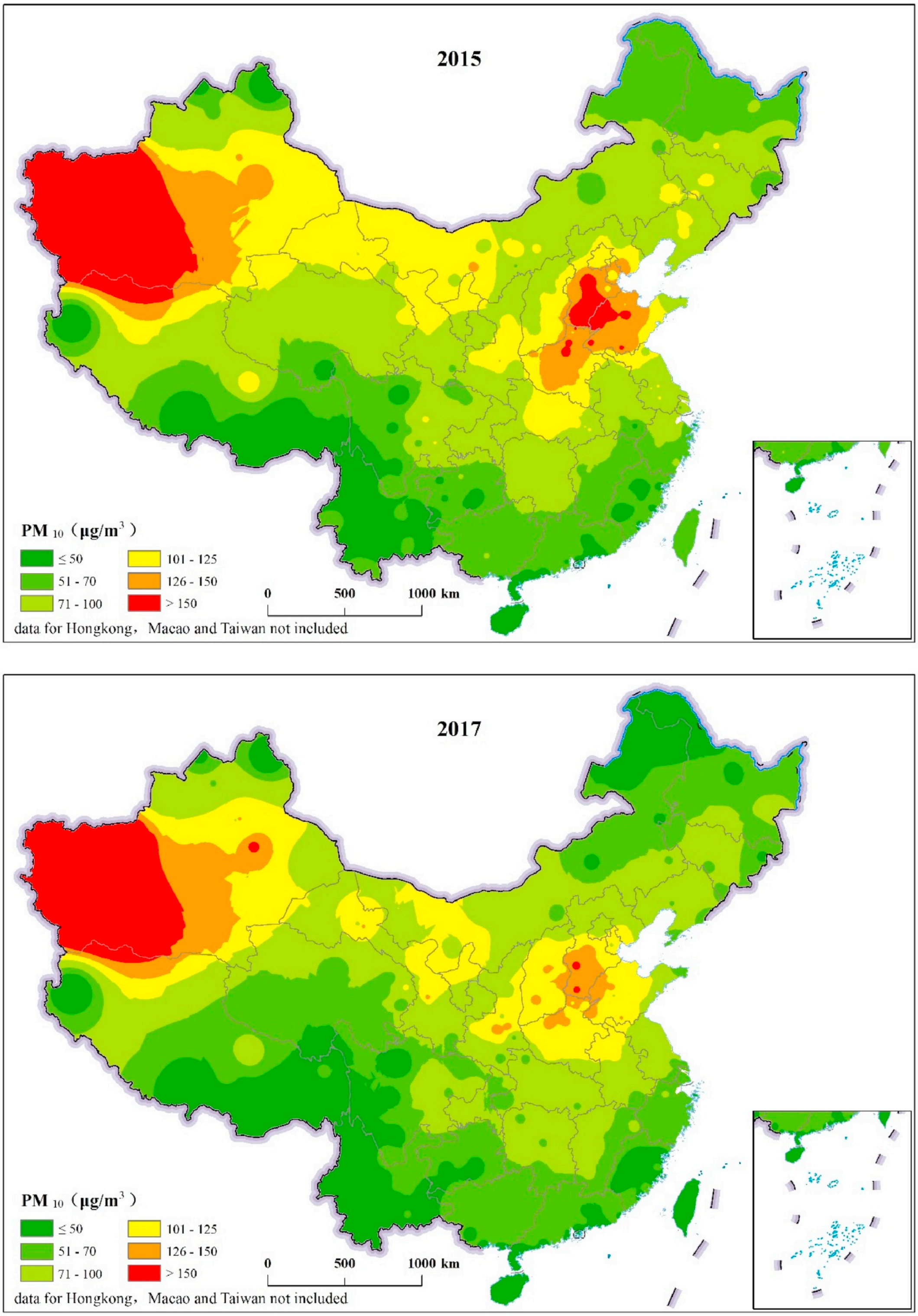

Fig. 5. (*continued*).

Zhejiang and Shanghai, central and northern parts of Jiangxi, central and northern parts of Fujian, central and eastern parts of Hunan, central parts of Guangdong, southern parts of Chongqing, southern parts of Jiangsu, and some areas of Anhui (Fig. 9).

4.5. Air pollution prevention and control in China

The nationwide downward trend in pollutant concentrations is related to the increasingly strict restrictions and measures imposed by local governments and international organizations (Wang and Hao, 2012; Wu et al., 2015; Zhang et al., 2017). Measures adopted for the prevention and control of air pollution have undergone profound change over the previous few decades, especially in relation to the transition from weak to strong implementation (Jin et al., 2016; Zhang et al., 2016b). Recently, air pollution in China has evolved into an issue of wide and politically prioritized concern. Generally, the evolution of the

Table 1
Statistics on cities failing to meet the national Ambient Air Quality Standard (GB3095-2012) of $PM_{2.5}$ (2014–2018).

Year	Number of cities monitoring on $PM_{2.5}$	Number of cities failed to meet national air quality standard of $PM_{2.5}$	Ratio of cities failed to meet national air quality standard
2014	161	143	88.8
2015	338	262	77.5
2016	338	243	71.9
2017	338	217	64.2
2018	338	190	56.2

prevention and control of air pollution in China can be divided into four periods ((see details in Appendix Table 3)).

The first National Conference on Environmental Protection of the State Council in 1973 symbolized the first period (1973–1990), during which work on the prevention and control of air pollution focused on the control of industrial point sources. In this period, the main effort of atmospheric pollution prevention and control was directed toward transforming boilers, eliminating smoke and dust, and stopping point source emissions of air pollution. In the 1980s, the "People's Republic of China Air Pollution Prevention Law" (hereafter, the "Air Act") was formally promulgated. It established basic principles for the prevention and control of air pollution related to coal combustion. Thus, work on the prevention and control of air pollution changed from the control of point source emissions to an approach that was more comprehensive. The main work during this period combined national economic adjustment, changes to the structure and layout of cities, and the development of plans for air pollution prevention and control. Specifically, industrial pollution was prevented and treated through a combination of technological transformation and comprehensive utilization of resources. The integrated prevention and control of air pollution related to coal combustion was achieved through energy saving and changes to the urban energy structure, which involved the closing, merging, transferring, or moving heavy polluting enterprises through adjustment of the industrial structure and distribution. The above measures played a key role in controlling the sharp deterioration of the atmospheric environment, which was reflected in the decrease of the national annual average concentration of TSP by 44.2%.

The second period of evolution covered the 1990s. During this time, work on the prevention and control of air pollution entered a new historical stage. It shifted from control of the concentrations of air pollutants to control of the total amount of emissions from pollution sources, and from integrated improvement of the urban environment to control of regional pollution. A considerable amount of work was undertaken on the formulation of laws and regulations, establishment of supervisory and management systems, reinforcement of air pollution control measures, development and extension of pollution control technology, and many other aspects, which promoted the prevention and control of atmospheric PM matter pollution. The State Council proposed and approved corresponding supporting policies on the "Two Control Zones" partitioning scheme that focused on the control of SO_2 and acid rain pollution. The partitioning of the Two Control Zones not only promoted comprehensive work on the prevention and control work of acid rain and SO_2, but it also played an important role in the process of control of atmospheric PM pollution. At the national level, TSP pollution improved annually during the second period, i.e., the national average annual TSP concentration decreased by 32.7%, which laid the foundation for the prevention and control of PM_{10} pollution.

The third period extended from 2000 to 2012, which is when ambient air pollution control in China entered a new phase that focused on control of the total amount of emissions of major pollutants. The Air Act received a second amendment in April 2000. The new law stipulated total emission amounts and it introduced a permit system for the discharge of pollutants in key environmental protection areas. Under this new system, excessive discharge of pollutants was illegal and charges could be made in accordance with the type and quantity of pollutants emitted. Furthermore, the new regulations enhanced efforts to control vehicular pollution, proposed the delineation of key air pollution control cities and regulations on compliance deadlines, and strengthened measures for the prevention and control of urban dust pollution. During the first decade of the 21st century, the focus of national atmospheric PM pollution prevention and control changed from TSP to PM_{10}, and national annual PM_{10} concentration decreased by 45.6% annually. Attention on $PM_{2.5}$ pollution emerged gradually after 2010.

The fourth period, which began in 2013, extended through the 12th Five-Year Plan (short for Outline of the Five-Year Plan for National Economic and Social Development of China, similarly hereinafter). During this time, the prevention and control of air pollution entered a new "transition stage" guided by the principles of sustainability and energy conservation and driven by intensified societal pressure (MEP, 2017, MEP, 2018; MEE, 2018, MEE, 2019a, 2019b, 2019c). The State Council printed and circulated the Action Plan on Prevention and Control of Atmospheric Pollution (hereafter, the "Action Plan") in 2013, which incorporated 35 comprehensive control measures in 10 Articles. Accordingly, a regional cooperation mechanism was devised to address atmospheric pollution in the BTH region and surrounding area, as well as in the YRD region. Measures were adopted to address improvements of key industries, industrial restructuring, better energy structure, and vehicular exhaust control. Moreover, the Clean Air Research Initiative was started. In 2014, the State Council printed and distributed the Performance Assessment Measures for the Action Plan for Air Pollution Prevention and Control (Trial), which specified 19 policy measures and 20 pollutant emission standards. During 2015, the MEP deepened regional coordination and it included Henan Province and the Ministry of Transport in the mechanism for joint prevention and control of pollution in the BTH region and surrounding area. Importantly, the MEP introduced comprehensive measures for the control of volatile organic compounds (VOCs) in petrochemical industry. In 2016, China introduced a reinforced Action Plan for the BTH region (2016–2017). This plan promoted the optimization and adjustment of the energy structure, reduction of VOCs in key sectors, and the off-peak production of cement.

In 2017, the air pollution improvement objectives and key tasks specified in the Action Plan were fulfilled. Subsequently, the MEP launched a project for the analysis and control of heavy atmospheric pollution, and it conducted comprehensive management of atmospheric pollution in autumn and winter in the BTH region and surrounding areas.

5. Discussion

In this study, the history of the monitoring of ambient air quality in China during 1981–2018 was summarized. The determinants, monitoring extent, monitoring methods, ambient air quality standards, and requirements regarding data validation were also considered. The evolution of measures adopted for the prevention and control of air pollution was discussed, and the spatiotemporal patterns of ambient air quality during the previous four decades were analyzed. To our knowledge, this represents the first systematic study of the monitoring history and spatiotemporal patterns of ambient air quality in China since the start of the Reform and Opening-Up in 1978. Our results should provide valuable information regarding air quality monitoring for the public, researchers, and government. Moreover, the findings will provide environmental and scientific evidence to support informed decisions on measures proposed for the prevention and control of air pollution and related polices, and provide reference information for related environmental research.

The results showed that since the start of the Reform and Opening-up (1978), China's socioeconomic development, recent technological advances, and changes in the status of particulate pollution have meant that monitoring of atmospheric PM has changed dramatically in terms of

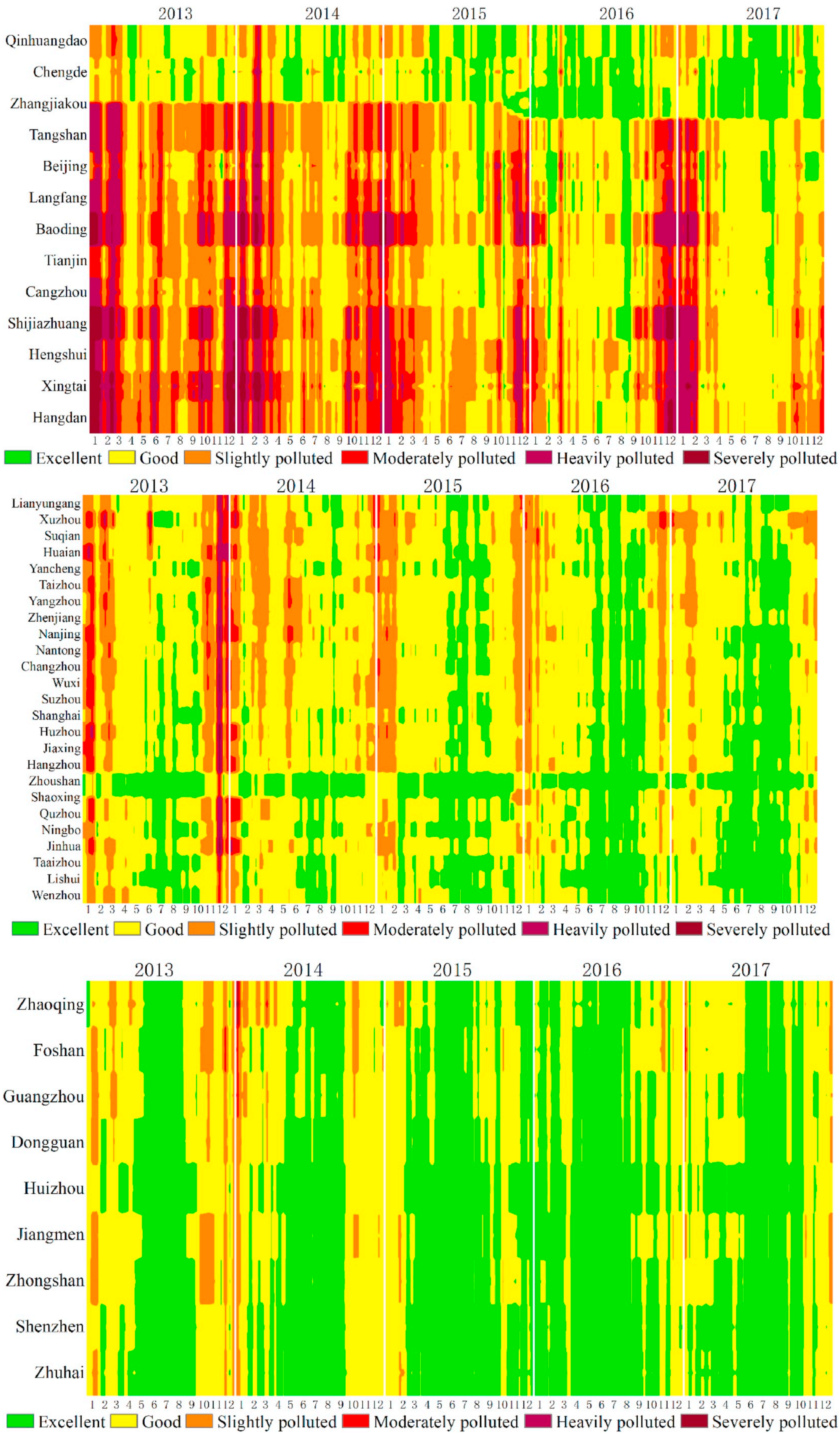

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Fig. 6. Spatiotemporal distribution of daily $PM_{2.5}$ concentrations in the BTH, YRD, and PRD regions during 2013–2017. According to the Ambient Air Quality Standard (GB 3095-2012) and Technical Regulation on Ambient Air Quality Index (HJ 633-2012), a $PM_{2.5}$ concentration of limit value I ($\leq$35 μg/m^3) means excellent air quality, limit value II (35 < concentration $\leq$75 μg/m^3) means good air quality, limit value III (75 < concentration $\leq$ 115 μg/m^3) means slightly polluted air quality, limit value IV (115 < concentration $\leq$ 150 μg/m^3) means moderately polluted air quality, limit value V (150 < concentration $\leq$ 250 μg/m^3) means heavily polluted air quality, and limit value VI (>250 μg/m^3) means severely polluted air quality.

the monitoring items, sampling methods, scope of monitoring, and basis for evaluation. Concentrations of TSP and the annual amount of dust both showed trends of decrease during 1981–2000. Overall, the annual average concentration of PM_{10} presented a downward trend during 2000–2018. In comparison with 2005, the national level of PM_{10} pollution had clearly been mitigated by 2018, and the area of the country suffering heavy pollution had been reduced considerably. Since 1981, the annual average SO_2 concentration has shown an obvious and continuous trend of decrease, acid rain pollution has been mitigated significantly, and the area affected by acid rain has clearly been reduced. These improvements have been related closely to the various approaches and tremendous efforts of the Chinese government toward the prevention and control of ambient air quality (Jin et al., 2016; Liu et al., 2014; MEE, 2018; MEP, 2017; Wang et al., 2018; Zhang et al., 2011b), especially in recent years. The government has attached great importance to the control and alleviation of air pollution through a series of regulatory policies, e.g., the new Ambient Air Quality Standard issued in 2012, the Action Plan published in 2013, and the campaign to defend the blue sky, the results of which have been fruitful and remarkable.

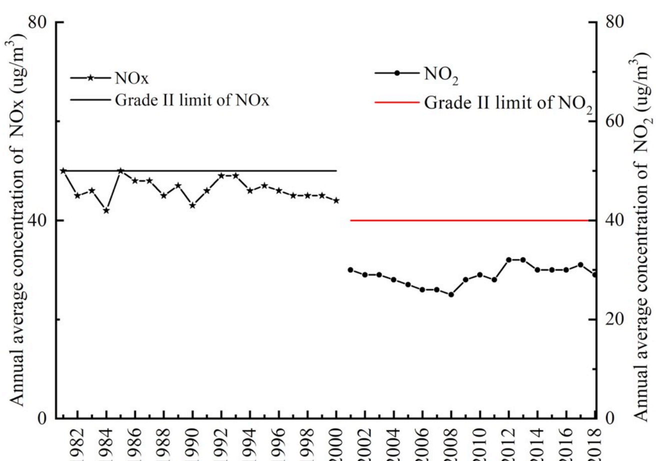

Fig. 7. Temporal trends of NO_X and NO_2 concentrations in China during 1981–2018.

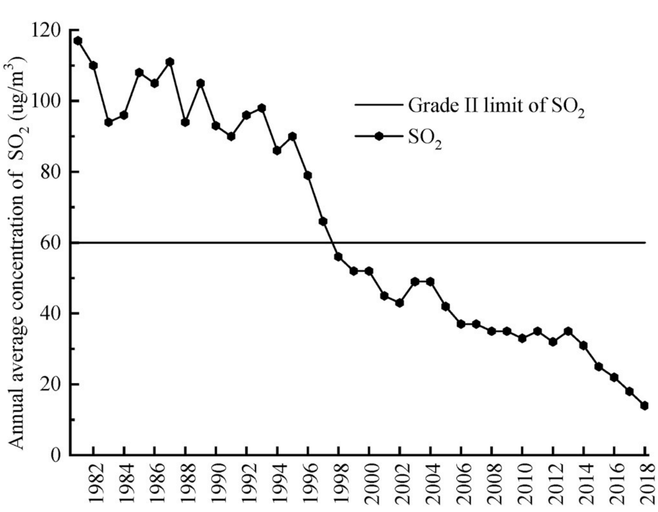

Fig. 8. Temporal trend of SO_2 concentration in China during 1981–2018.

During the study period, ambient air quality has improved continuously, with a steady increase in the number of attainment days and decreases in the concentrations of the principal air pollutants, especially $PM_{2.5}$ (Jin et al., 2016; Wang et al., 2016).

In 2017, the average concentration of PM_{10} in the 338 monitoring cities in China was 22.7% lower than in 2013, and the average $PM_{2.5}$ concentration in the BTH, YRD, and PRD regions was 39.6%, 34.3%, and 27.7% lower, respectively, than in 2013. The average concentration of $PM_{2.5}$ in Beijing dropped from 89.5 μg/m^3 in 2013 to 58 μg/m^3 in 2017 (MEE, 2018, 2019a, 2019b, 2019c).

Despite the considerable recent improvements, the current situation regarding air quality remains of concern. Although the implementation of mitigating measures has been decisive and, at least in part, enforced effectively, considerable challenges remain with regard to the control of industrial and vehicular emissions. National air quality limits continue to be exceeded and frequent episodes of heavy air pollution still occur (Wang et al., 2018; Zhai et al., 2018), which have serious consequence for public health and wellbeing (Bai et al., 2018; Liu et al., 2018; Maji et al., 2018). For example, in the BTH region, the annual average $PM_{2.5}$ concentration in 2013–2017 was 106, 93, 77, 71, and 64 μg/m^3, respectively, i.e., more than 2.03, 1.66, 1.2, 1.02, and 0.83 times the Grade II limit for $PM_{2.5}$ (35 μg/m^3) (MEE, 2018; MEP, 2017).

In 2017, 99 of the 338 cities across China that conducted environmental monitoring met the national air quality standard,[2] accounting for 29.3% of the total number of cities. Conversely, 239 cities (70.7% of the total) failed to meet the national air quality standard. Of these, 48 cities suffered heavy or severe pollution on more than 20 days. The average percent of days of air quality attainment of the 338 cities was 78.0%, i.e., down by 0.8% compared with 2016, while the percent of non-attainment days was 22.0% (MEE, 2019a, 2019b, 2019c).

During the studied period, the major source of air pollution transferred from that associated solely with coal combustion to the combination of coal combustion and chemical pollution. Regional heavy air pollution occurred in some areas, and obvious regionally complex $PM_{2.5}$ pollution in winter and complex ozone pollution in summer was evident in the BTH, YRD, and PRD regions and some other urban groups, which restricted sustainable regional socioeconomic development considerably (Fig. 10) (MEE, 2018, 2019a, 2019b, 2019c).

To comprehend fully the air pollution situation in China, it is necessary to understand the complex factors that affect pollution. Most natural factors—including topographic relief, annual average temperature, annual average precipitation, and relative humidity, but excluding wind speed, sunshine hours, and air pressure—show significant negative associations with air pollution in China, while all human factors except the urbanization rate have significant positive correlation with air pollution (Chen et al., 2017, 2018; Zhan et al., 2017; Zhao et al., 2018a). Specifically, high emissions of atmospheric pollutants that far exceed the environmental carrying capacity are the fundamental reason for air pollution (Feng et al., 2018; Liu et al., 2017; Pu et al., 2018). In 2015, the emissions of SO_2, NO_X, smoke dust, VOCs, and atmospheric ammonia reached 18.59×10^6, 18.52×10^6, 15.38×10^6, 30×10^6, and 10×10^6 t, respectively (MEP, 2016; NBSPRC, 2016). According to estimates, to achieve significant improvement in China's ambient air quality, it will

[2] Air quality meeting the standard: the ambient air quality is considered to meet the standard when the concentrations of all six pollutants under assessment meet the standard. Of the pollutants, SO_2, NO_2, PM_{10}, and $PM_{2.5}$ were evaluated based on the annual average concentration, and CO and O_3 were evaluated based on percentile concentrations.

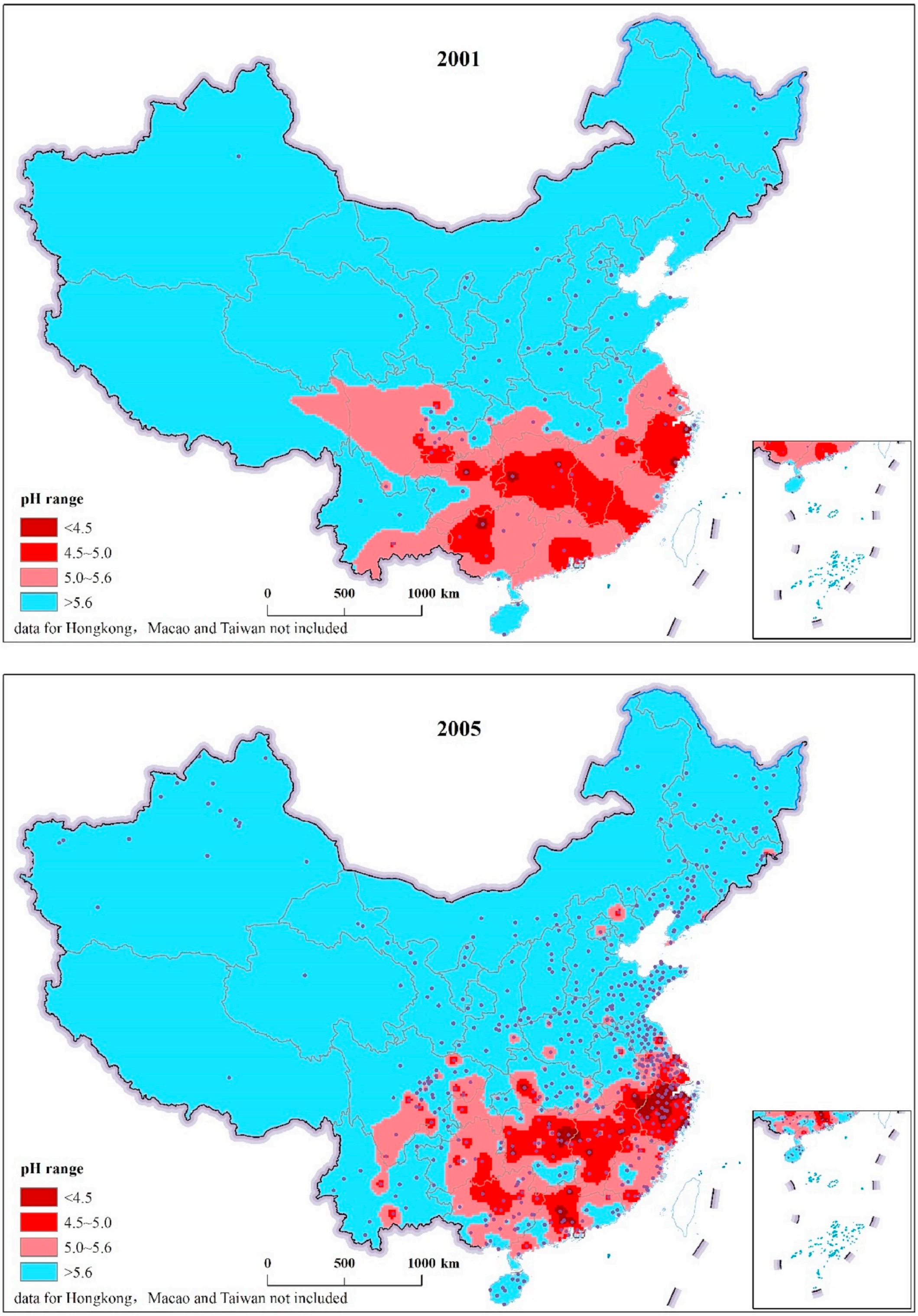

Fig. 9. Spatial distribution of areas affected by acid rain in China from 2001 to 2017.

be necessary to reduce the emissions of major pollutants by more than 50% (Ding et al., 2017). Consequently, regional governments in northern China should consider imposing stricter environmental regulations and designing adequate emergency measures to address the serious and persistent air pollution episodes that occur mostly during winter months (Zhang et al., 2017).

Persistent meteorological conditions that not conducive to the dispersal of pollution can make the air pollution situation in China more severe and complicated (Liu et al., 2016b, 2017; Zhao et al., 2018c). In recent years, strengthening of the El Niño phenomenon has created abnormal climate patterns. For example, incursions of cold air across northern China have been less frequent, with weaker intensity, and lower wind speeds. In particular, the mixed layer of the atmosphere has been lowered, and the air temperature and humidity have been higher

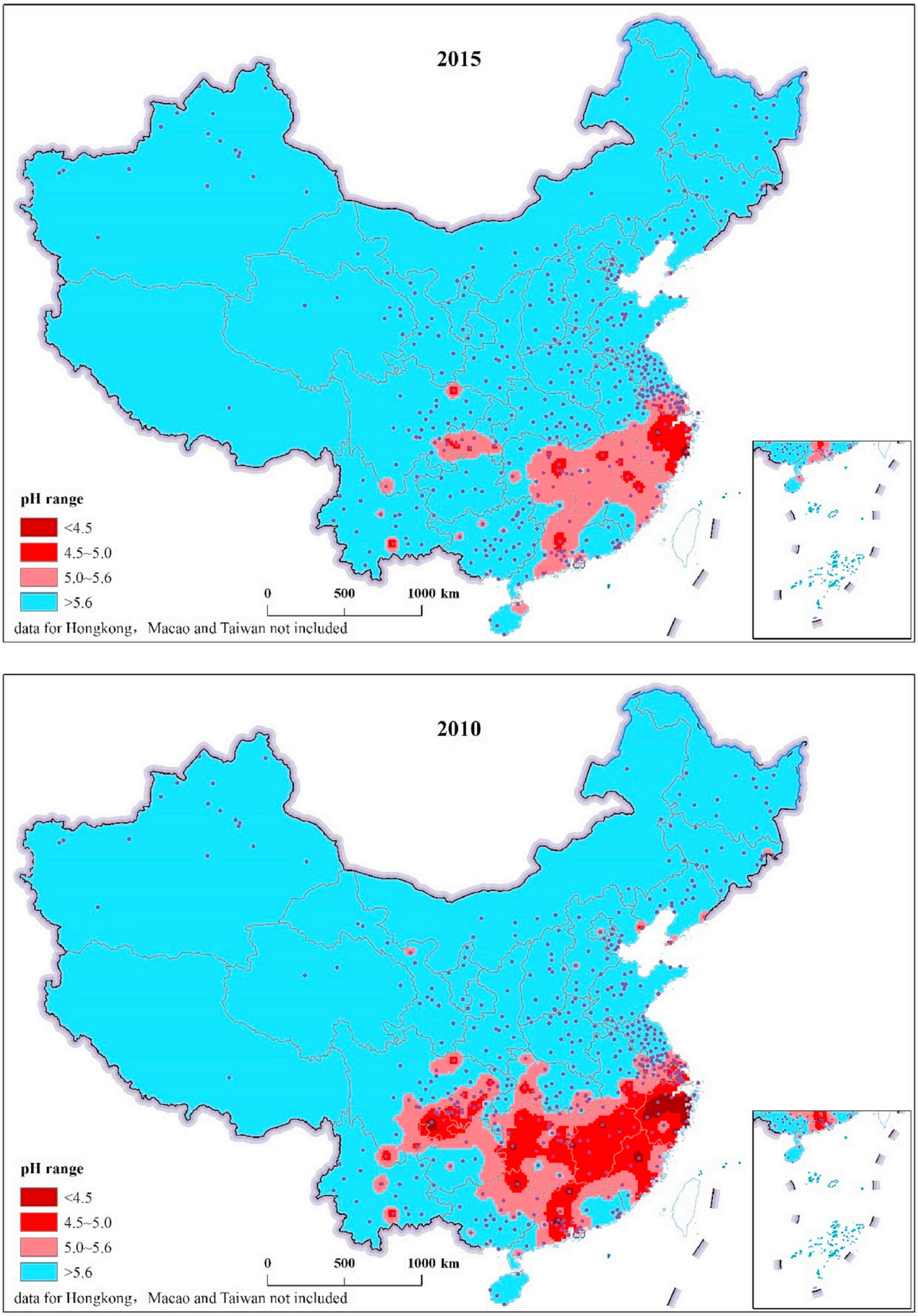

Fig. 9. (*continued*).

than normal, creating conditions unfavorable for the diffusion of pollutants, and accelerating the secondary generation of $PM_{2.5}$ and increasing pollution levels (Zhao et al., 2018a, 2018c).

Control of air pollution involves complex economic and social factors that must be addressed over the long term (Zeng et al., 2017). It took 20–40 years for developed countries to solve their problems regarding air pollution. Therefore, China should retain its confidence and not expect a quick fix. Tackling air pollution represents a long-term struggle; however, China can exploit its latecomer advantage and draw on the experience of governments in developed countries. Under the strong leadership of the Party Central Committee and the State Council, together with the concerted effort of the public, it will be possible to resolve China's current atmospheric environmental problems expeditiously.

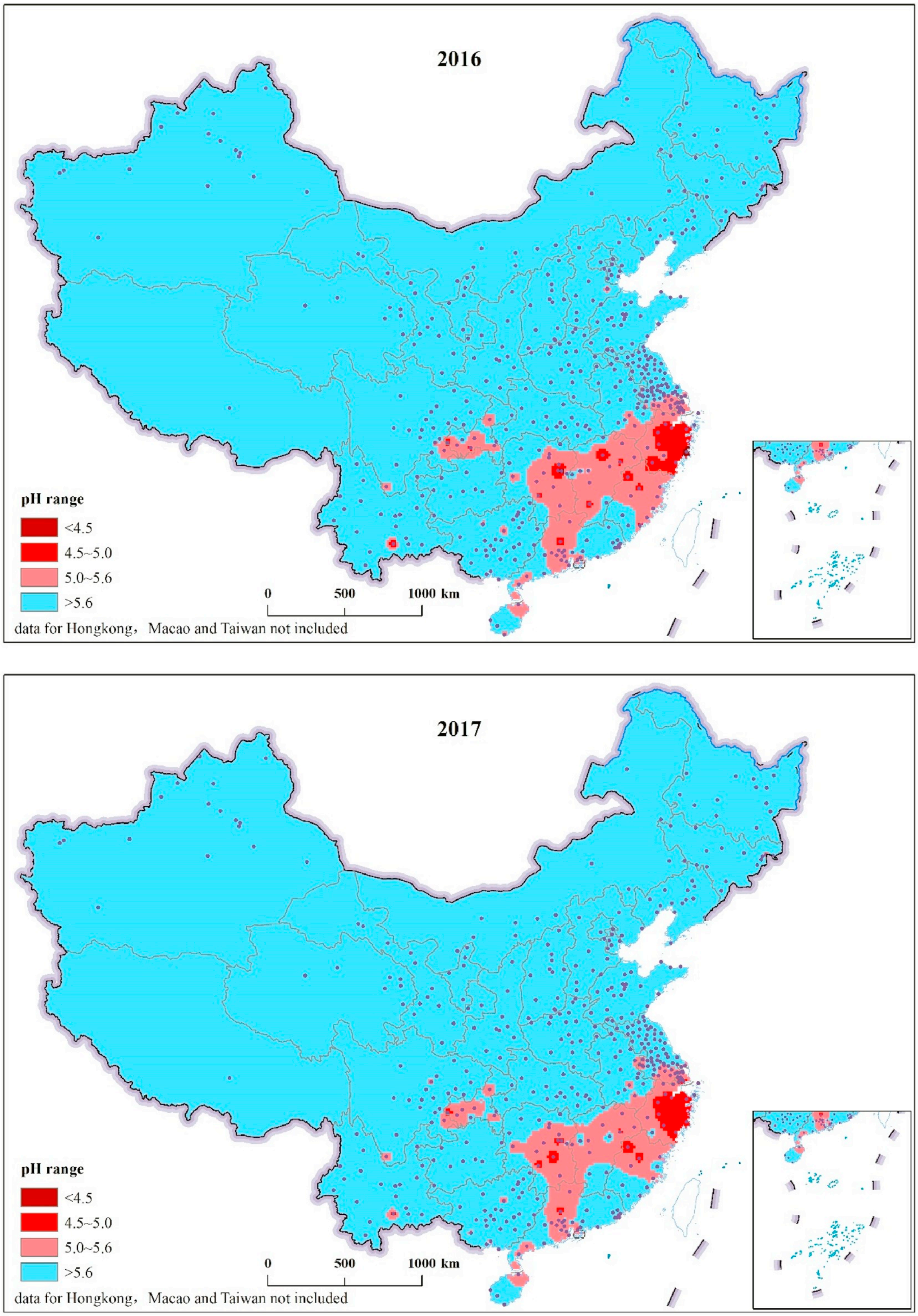

Fig. 9. (*continued*).

6. Conclusions

After 40 years' development, China has established the national ambient air quality monitoring network, which is the largest air quality monitoring network in the developing countries. Monitoring of ambient air quality in China has followed a path of gradual transition from less to more and from coarse particles to fine PM. Monitoring of air pollutants in China has evolved from a manual process into comprehensive automatic monitoring. The ambient air quality has become more strictly, and the data has become more accurate and representative.

Lots efforts have been down on improving the air quality in China, with measures adopted for the prevention and control of air pollution have transited from weak to strong implementation; and the ambient air quality also improved by time. The annual average TSP concentration decreased from 1981 to 2000; the annual average PM_{10} concentration showed a continued trend of decrease during 2000–2017; the acid rain

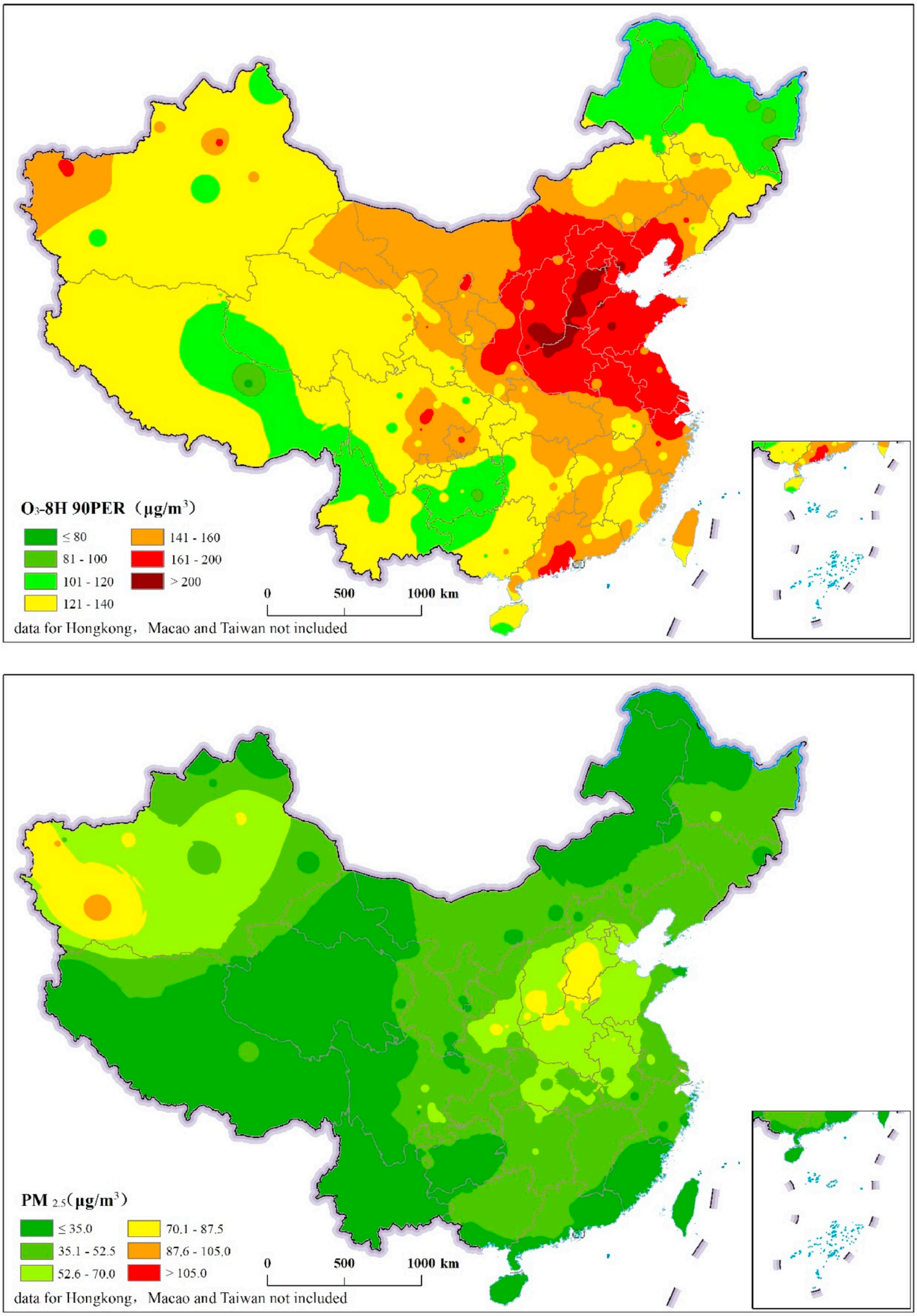

Fig. 10. Spatial distributions of $PM_{2.5}$ and O_3 concentrations in China in 2017.

pollution had been mitigated since 2001. Since 2013, air quality in China has improved greatly, with an obvious trend of decrease in the level of $PM_{2.5}$ in the entire country.

Declaration of competing interest

All authors declare to have no conflict of interest to disclose in the context with this study.

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Appendix

Table 1
Main structure of the national-level air quality monitoring network.

Category/Network	Sites	Indicators	Method
Urban air	1436 sites, 338 cities	SO_2, NO_2, PM_{10}, CO, O_3, $PM_{2.5}$, Five meteorological parameters, *visibility* etc	Automatic
Regional air	92 sites		
Background air	16 sites		
Acid deposition	440sites, 359 cities	precipitation, pH, EC, SO_4^{2-}, NO_3^-, F^-, Cl^-, NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, K^+)	Automatic
Sand storm and dust	78 sities, 78cities	TSP, PM_{10}, visibility, wind speed, wind direction	Automatic
Greenhouse gases	10 sities	CO_2, CH_4, N_2O	
PM composition	49 sities, 42 cities	$PM_{2.5}$, water-soluble ions, inorganic elements, OC/EC, online PM mass spectrometer characteristics	Automatic & manual
Photochemical	78 sites, 78 cities	Alkanes, Olefins, Aromatic hydrocarbons, Oxygen-containing volatile organic compounds, Halogenated hydrocarbons	Automatic & manual

Table 2
Ambient air quality standards in China.

Pollutant μg/m^3	Collecting time	GB3095-1982			GB3095-1996			GB3095-2012	
		Limit			Limit			Limit	
		Grade I	Grade II	Grade III	Grade I	Grade II	Grade III	Grade I	Grade II
	anytime of a day	300	1000	1500					
TSP	24 h	150	300	500	120	300	500	120	300
	annual				80	200	300	80	200
	anytime of a day	150	500	700					
PM_{10}	24 h	50	150	250	50	150	250	50	150
	annual				40	100	150	40	70
$PM_{2.5}$	24 h							35	150
	annual							15	70
SO_2	anytime of a day	150	500	700					
	hourly				150	500	700	150	500
	24 h	50	150	250	50	150	250	50	150
	annual	20	60	100	20	60	100	20	60
NO_2	anytime of a day	100	150	300					
	hourly				120	120	240	200	200
	24 h	50	100	150	80	80	120	80	80
	annual				40	40	80	40	40
CO	anytime of a day	10000	10000	20000					
	hourly				10000	10000	20000	10000	10000
	24 h	4000	4000	6000	4000	4000	6000	4000	4000
O_3	hourly	120	160	200	120	160	200	160	200
	daily 8-h maximum							100	160

Note: GB3095-1996, Grade I for areas such as nature reserves and other areas that need special protection. Grade II is the standard for mainly residential area, commercial areas and mixed use urban areas as well as the rural areas. Grade III standard applies to specific industrial zones. GB3095-2012, Grade I standards apply to special regions such as national parks. Grade II standards apply to all other areas, including urban and industrial areas.

Table 3
Development of air pollution prevention and control in China

Period	1973–1990	1991–2000	2000–2012	2013~
Main pollution sources	Coal-burning, industry	Coal-burning, industry, dust	Coal-burning, industry, vehicle, dust	Coal-burning, industry, vehicle, combined pollution sources
Principal pollutant	SO_2, TSP	SO_2, NO_X, TSP	SO_2, PM_{10}, NO_X, investigation work on VOC, NH_3 and $PM_{2.5}$ was conducted in some cities	$PM_{2.5}$, PM_{10}, O_3
Air pollution scale	Local	Local plus regional	Regional plus national	Regional plus national
Main air pollution problem	Smoke from coal burning	Smoke from coal burning, acid rain, particulate matter	Smoke from coal burning, acid rain, photochemical pollution, haze/fine particulate matter, toxic or harmful substances	haze/fine particulate matter, ozone pollution, combined pollution

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Table 3 (*continued*)

Period	1973–1990	1991–2000	2000–2012	2013~
Main regulations measure	smoke prevention and dust control	smoke prevention and dust control, transformation/shut off/comprehensive upgrading	desulfuration and dedusting, pollution abatement, vehicle management, total quantity control	Action Plan on Prevention and Control of Atmospheric Pollution (2013-2017)

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