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# Characteristics and health impacts of particulate matter pollution in China (2001–2011)

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## HIGHLIGHTS

► Characteristics and health impacts of $PM_{10}$ pollution in China were evaluated.
► $PM_{10}$ pollution in China has been reduced during the last decade.
► PM pollution (especially fine particles) is still a severe environmental problem.
► Great health benefit is achieved due to $PM_{10}$ reduction.
► The absolute damage cases are increasing due to the increase in urban population.

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## ABSTRACT

In this study, a systematic overview of inhalable particulate matter ($PM_{10}$) pollution in China was conducted based on the dataset from national monitoring network from 2001 to 2011. The long-term trend, spatial and temporal distributions, and health impacts of $PM_{10}$ pollution were evaluated. It was found that the annual $PM_{10}$ concentration decreased from 116.0 μg $m^{-3}$ in 2001 to 85.3 μg $m^{-3}$ in 2011. The days with $PM_{10}$ concentration above the new Chinese ambient air quality standard dropped from 66 (18%) in 2001 to 28 (7.8%) in 2011, while the days exceeding the World Health Organization (WHO) guideline decreased from 294 (80.5%) in 2001 to 250 (68.5%) in 2011. $PM_{10}$ pollution in northern China is much worse than that in southern China. Six of nine most polluted cities (>110 μg $m^{-3}$) are in the north, while six cleanest cities (<50 μg $m^{-3}$) are all in the south. The seasonal average $PM_{10}$ concentrations in 2001–2011 for all cities are 104.4 μg $m^{-3}$ (spring), 75.3 μg $m^{-3}$ (summer), 94.7 μg $m^{-3}$ (autumn), and 118.4 μg $m^{-3}$ (winter), respectively, indicating that winter and spring are the most polluted seasons. Different health endpoints due to $PM_{10}$ pollution show similar trends. Taking premature mortality between 2001 and 2011 as an example, the ratio of deaths due to $PM_{10}$ pollution to all causes of deaths dropped from 13.5% to 11.6% and 511,000 deaths are avoided due to the concentration reduction, though the absolute damage number due to $PM_{10}$ pollution increased from 418,000 to 514,000 because of increasing urban population. These results indicate that $PM_{10}$ pollution in China has been eased significantly over the last decade, mainly due to the application of emission control measures. However, the $PM_{10}$ concentration remains at a high level comparing with the WHO guideline and its health impacts are still significant.



## 1. Introduction

The high intensity of pollution emissions has caused severe air quality problems in China, especially in the eastern region since the 1980s. According to the 2005 data from the World Bank, sixteen of the twenty-two most polluted cities in the world are located in China (World Bank, 2007). Only 1 percent of the whole country's urban population lives in cities with an annual average level of particulate matter (PM) with aerodynamic diameter of 10 μm or less ($PM_{10}$) below 40 μg $m^{-3}$ (World Bank, 2007). The emission from China is much greater than those from any other countries, both for primary particulate matter (Bond et al., 2004) and for gaseous pollutants (Akimoto, 2003; Ohara et al., 2007). From satellite observation results derived from the MODIS platform, aerosol optical depth (AOD) is approximately 0.5–0.8 in eastern China (Wang et al., 2011c), and the inverted concentration of fine particulate matter with an aerodynamic diameter equal to and less than 2.5 μm ($PM_{2.5}$) in eastern China has a value over 80 μg $m^{-3}$

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(van Donkelaar et al., 2010). High aerosol loading in China not only impairs the visibility significantly (Zhang et al., 2012a), but also causes public health damage. It is estimated that the economic burden of health damage due to air pollution as part of the total GDP was 1.2% in 2003 (World Bank, 2007) and 5% in 2005 (Matus et al., 2012).

Most previous studies of long-term PM pollution in China are based on either AOD data from ground monitoring (Wang et al., 2011c), satellite observations (Guo et al., 2011; Lin et al., 2010) or manual visibility observations (Chang et al., 2009; Che et al., 2009). These indices are often influenced by weather conditions with large uncertainties, and they cannot reflect ground air pollution status directly. Since June of 2000, the Chinese government started to publish a daily air pollution index (API) for national key cities based on ground monitoring. The so-called "API" is an integrated index obtained from the daily average concentrations of sulfur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), and $PM_{10}$. Comparing with satellite observation, ground monitoring provides a direct measurement of $PM_{10}$ concentration and the monitoring sites are more representative of the real urban environment in China. Some elegant analysis using this dataset has been conducted (e.g., Qu et al., 2010). However, previous studies either focused on a rather short term like 2000–2006 (Qu et al., 2010; Yang, 2009) or only on some city clusters (Li et al., 2011; Wang and Gao, 2008). An overall evaluation of $PM_{10}$ pollution in China during the long period of 2001–2011 is needed.

Furthermore, there is a lack of trend evaluation of the health impacts of $PM_{10}$ in China. Over the last 20 years, studies in developed countries have demonstrated an association between mortality and morbidity and exposures to concentrations of pollutants including particulate matter (Anenberg et al., 2010; Nel, 2005; Pope and Dockery, 2006; Salma et al., 2002). Most of the health evidence on particulate matter has been derived from studies of human populations in urban areas, showing adverse health outcomes such as hospital admissions for cardiovascular and respiratory disease, urgent care visits, asthma attacks, acute bronchitis and restrictions in activity.

China released a new ambient air quality standard in 2012 which lowers the previous threshold value of $PM_{10}$ and includes an index of $PM_{2.5}$ for the first time. The evaluation of the PM pollution situation in China will facilitate the implement of the new air quality standard. The long-term API-based official datasets (2001–2011) were analyzed in this study. We report the historical trend and the characteristics of particulate matter pollution in China, the challenge to attain the new standard and to meet the WHO guideline, and the estimation of health impact due to $PM_{10}$ pollution.

## 2. Data sources and methodology

Daily $PM_{10}$ concentrations for 86 national key cities on environmental protection from 2001-1-1 to 2011-12-31 are used for this study. The national key cities on environmental protection are those selected as a member of the national air quality monitoring network by the Ministry of Environmental Protection of China (MEP) according to factors such as population, gross domestic product, and location. MEP publishes daily primary pollutant name along with its air pollution index (API) for all national key cities in its official website (http://datacenter.mep.gov.cn). This integrated index is calculated from the daily average concentrations of $SO_2$, $NO_2$, and $PM_{10}$ (Ministry of environmental protection, 2008). Based on the same principle, one can estimate the daily $PM_{10}$ concentration from the API value when the daily primary pollutant is $PM_{10}$. Linear interpolation is performed between each set of threshold values. There is no $PM_{10}$ concentration for the day when the primary pollutant is $SO_2$ or $NO_2$. This method has been used in previous studies (e.g., Feng et al., 2011; Qu et al., 2010; Yang, 2009; Zhang et al., 2012b).

The number of key cities included in the dataset has increased several times during last decade. There are 47 cities between 2001 and 2003, 84 cities from 2004 to 2005, 86 cities from 2006 to 2010, and 120 cities for 2011. In 2004, although the number of cities increased from 47 to 84, the datasets of 37 new cities are not included in this study due to the absence of records in the first five months of 2004. Fig. 1 shows the geographic locations of these key cities colored by their starting year. The cities cover all provinces in China, especially the urbanized areas of eastern China which is thought to be more polluted.

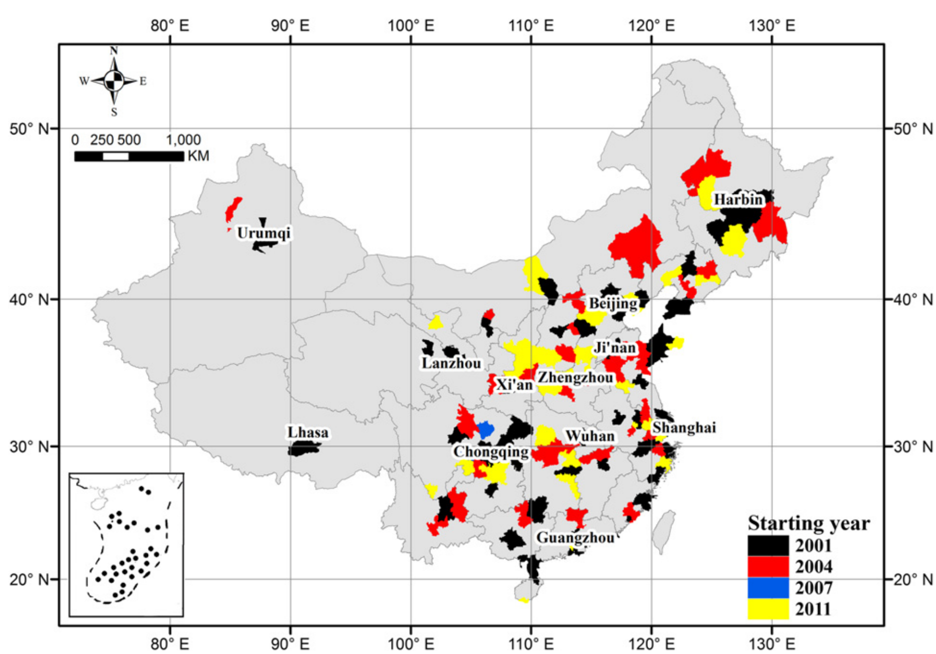


**Fig. 1.** Geographic location of the national key cities on environmental protection.

The days on which the primary pollutant is $PM_{10}$ are calculated for each city and each year (Fig. 2). It can be seen that over 320 days (88% of the whole year) have $PM_{10}$ as the primary pollutant for the average of all cities for all the years. Because of the dominant ratio of the number of days with $PM_{10}$ as the primary pollutant, it is thought that the derived $PM_{10}$ concentration for each city can represent the general $PM_{10}$ pollution status. As shown in Fig. 2, the number of key cities included in the following analysis (e.g., the long-term trend and temporal distributions) increased in 2005, 2006, and 2011. We compared it with the analysis only using the original 47 cities and no significant difference was observed.

Three types of ambient air quality standards are selected for assessing the above dataset, i.e., the China national ambient air quality standards published in 1996 (CNAAQS (1996)) and 2012 (CNAAQS (2012)) and WHO air quality guideline published in 2005. The annual and daily $PM_{10}$ concentrations of CNAAQS (1996) for Class II are 100 $\mu g\ m^{-3}$ and 150 $\mu g\ m^{-3}$, respectively. The annual and daily values of CNAAQS (2012) for Class II are 70 $\mu g\ m^{-3}$ and 150 $\mu g\ m^{-3}$, respectively. WHO air quality guideline for annual and daily values are 20 $\mu g\ m^{-3}$ and 50 $\mu g\ m^{-3}$, respectively.

The quantitative health impact assessment (HIA) of outdoor air pollution is based on four components: (1) Ambient exposure of the population to $PM_{10}$, obtained from the daily $PM_{10}$ concentration values of the national key cities. (2) Population exposed to the $PM_{10}$, obtained from the China Statistical Yearbook compiled by the National Bureau of Statistics of China. The values were calculated for the urban fraction of the whole national population. (3) The incidence of the health effect being estimated, obtained from the China Health Statistical Year book compiled by the Ministry of Health of China. (4) Concentration–Response functions, compiled from the epidemiological literature that relates $PM_{10}$ concentrations to health effects.

It is known that $PM_{10}$ cannot cover particulate matter's health impacts completely, as $PM_{2.5}$ poses greater risk to public health because it could lodge deeply in the lungs and remains for longer periods. However, the use of $PM_{10}$ as the indicator could give a general estimate as there is currently no regular $PM_{2.5}$ monitoring data in China.

Four health endpoints are selected to assess the health impacts caused by $PM_{10}$ pollution: premature mortality, respiratory and cardiovascular hospital admissions and chronic bronchitis. Relative risk (RR) for premature mortality is calculated as follows:

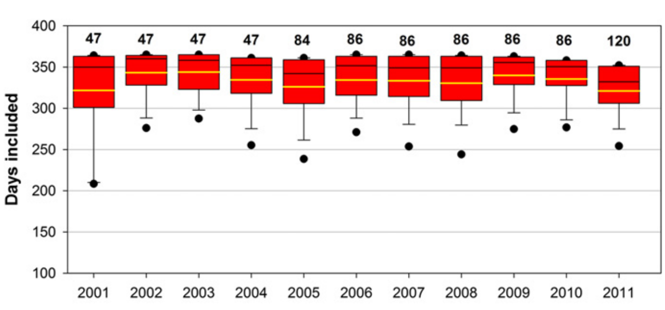


**Fig. 2.** Days with $PM_{10}$ as the primary pollutant for all monitored cities. The bottom and top of the box represent the 25th and 75th percentile respectively, i.e., 50% of cities are within the box; the black line and yellow line in the box represents the 50th percentile (the median) and mean value; the ends of the whiskers represent the 10th and 90th percentile; and the solid dots represent the 5th and 95th percentile; the numbers above each box are the number of cities included for that year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$\mathrm{RR} = ((C+1)/16)^{\beta} \tag{1}$$

And for the other health outcomes:

$$\mathrm{RR} = \exp[\beta \cdot (C - C_0)] \tag{2}$$

where C is the ambient $PM_{10}$ concentration, $C_0$ is the reference $PM_{10}$ concentration with a value of 15 $\mu g\ m^{-3}$. $\beta$ is the empirical coefficient (the percentage increase in health effect per 1 $\mu g\ m^{-3}$ $PM_{10}$ increment), and its value is 0.073 (95% Confidence Interval (CI): 0.045, 0.101) for premature mortality (World Bank, 2007), 0.0007 (95% CI: 00005, 0.0009) for cardiovascular hospital admissions (Aunan and Pan, 2004), 0.0012 (95% CI: 0.0010, 0.0014) for respiratory hospital admissions (Aunan and Pan, 2004), 0.0048 (95% CI: 0.0044, 0.0052) for chronic bronchitis (World Bank, 2007), respectively.

The number of cases for each health endpoint attributed to air pollution ($E$) is calculated as follows,

$$E = \mathrm{AF} \cdot f_p \cdot P \tag{3}$$

where $P$ is the size of the exposed population (estimated as the urban population each year for all the cities included in the monitoring network); $f_p$ is the current incidence rate (obtained from the China Health Statistical Yearbook); and AF is the attributable fractions (calculated using the relative risks),

$$\mathrm{AF} = \left(\frac{\mathrm{RR}-1}{\mathrm{RR}}\right) \tag{4}$$

This method has been used in previous assessments (Dias et al., 2012; Glorennec and Monroux, 2007; World Bank, 2007) to evaluate the burden of $PM_{10}$ on human health in different locations around the world. In the report of World Bank (2007), a comprehensive study of the health impacts of air pollution in China was given, together with epidemiological studies carried out in the country since 1980s. Those health endpoints are the same ones used here because of the availability of exposure–response studies, incidence rates and also comparisons between results.

Some assumptions were used to carry out the HIA: (1) The $PM_{10}$ concentration used to calculate the RR each year is an average $PM_{10}$ concentration for all national key cities. However, an HIA was performed for 47 cities using their respective average concentrations each year (2001–2011) to verify the similarities. The four endpoints showed analogous trends to those of the global average concentration for all the cities. (2) For the estimation of hospital admissions, it was assumed that the share of patients being admitted to the hospital for cardiovascular or respiratory diseases resembles the share of people suffering from these two diseases among all sick people. (3) The estimation of the incidence of chronic bronchitis is approximated by dividing the prevailing rate by the average duration of the illness (23 years) which was used in the report of World Bank (2007).

## 3. Results and discussion

### 3.1. Long-term $PM_{10}$ trend for key cities

The annual $PM_{10}$ concentration in China from 2001 to 2011 is shown in Fig. 3. Based on the average for all recorded days, the concentration decreased from 116.4 $\mu g\ m^{-3}$ in 2001 to 85.3 $\mu g\ m^{-3}$ in 2011, at a rate of $\sim$3 $\mu g\ m^{-3}$ per year. The annual concentration has attained the Class II value of CNAAQS (1996) since 2005, but it is still much higher than the Class II value of WHO guideline and CNAAQS (2012). According to the current decreasing rate of

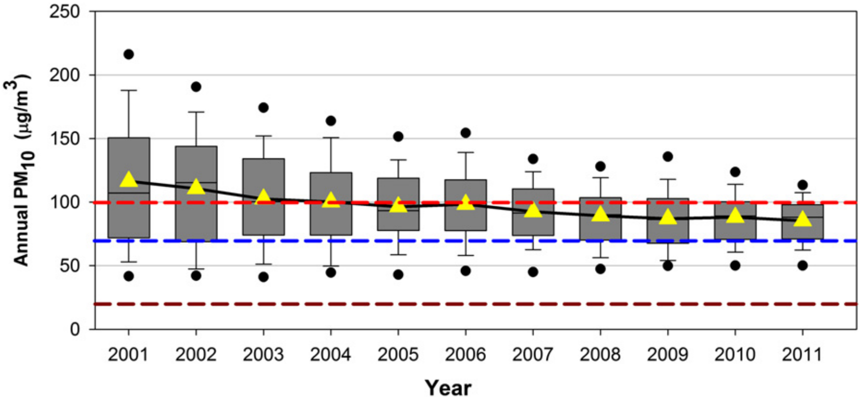


**Fig. 3.** Annual $PM_{10}$ concentration for key cities of China in 2001–2011. The yellow triangle represents the average value for all key cities, the bottom and top of the box represent the 25th and 75th percentile distribution for all key cities, respectively; the black line in the box represents the 50th percentile (the median) value; the ends of the whiskers represent the 10th and 90th percentile; and the solid dots represent the 5th and 95th percentile; the red long-dash solid line, blue long-dash line and brown long-dash line represents the Class II value of CNAAQS (1996), CNAAQS (2012) and WHO guideline respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3 μg $m^{-3}$ per year, five more years will be needed to attain the Class II value of CNAAQS (2012). However, it will become more difficult to maintain this decreasing rate as the ratio of $PM_{2.5}$ in $PM_{10}$ becomes higher with the reduction of $PM_{10}$ and the sources of $PM_{2.5}$ are more widespread and more difficult to control. Wang and Hao (2012) suggested that the effective control of primary coarse particle emissions could be offset by a dramatic increase in fine particle and its gaseous precursors which are from transportation and industry sources.

In general, 95th percentile, 50th percentile and 5th percentile levels shown in Fig. 3 could stand for the situations in the most polluted cities, the medium polluted cities, and the cleanest cities, respectively. The level of the most polluted cities decreased from 217 μg $m^{-3}$ in 2001 to 114 μg $m^{-3}$ in 2011, while that of the medium polluted cities decreased from 107 μg $m^{-3}$ in 2001 to 88 μg $m^{-3}$ in 2011. The level of the cleanest cities increased from 42 μg $m^{-3}$ in 2001 to 52 μg $m^{-3}$ in 2011. These results indicate that the condition of most polluted cities has been eased significantly, while the cleanest cities have not been well protected and are becoming slightly worse. If compared with the Class II value of CNAAQS (1996), the ratio of attained cities increases from 42% in 2001 to 75% in 2011, while compared with that of CNAAQS (2012), the ratio remained relatively stable at only 25% except for a slight decrease between 2004 and 2006. There is no key city included in the monitoring network that has attained the annual value of WHO guideline, indicating the wide gap that has to be filled to achieve the WHO air quality target.

The percentile distribution of all key cities for the number of polluted days when the daily concentration is above the daily Class II value of CNAAQS (2012) and WHO guideline is shown in Fig. 4. The cities with best air quality (5th percentile) in China can attain the Class II value of CNAAQS (2012) for almost all the days between 2001 and 2011. The polluted days for the cities with median air quality (50th percentile) decrease from 66 (18%) in 2001 to 29 (7.8%) in 2011, while the cities with worst air quality (95th percentile) decreased from 220 (60.3%) in 2001 to 64 (17.5%) in 2011. The general trend is similar to the annual concentration shown in Fig. 3, i.e., the situation of the most polluted cities improved rapidly, the concentration of the median cities decreased significantly and the number of the cleanest cities remained relatively stable. However, if compared with the daily value of WHO guideline, the polluted days increased substantially for all key cities. For the cities with best air quality (5th percentile), the polluted days over the value of WHO guideline increased from 50 in 2001 to 150 in 2011, indicating that the air quality in cleanest urban area has become worse. The polluted days for the cities with median air quality (50th percentile) decreased from 294 (80.5%) in 2001 to 250 (68.5%) in 2011, while for the cities with worst air quality (95th percentile), the polluted days decreased from 360 (98.6%) in 2001 to 340 (93.2%) in 2011. The number of polluted days over WHO guideline for most cities is very large, although there is a slight downward trend.

$PM_{10}$ source apportionment studies for Chinese cities indicate that $PM_{10}$ mainly originates from re-suspended dust and industrial coal combustion (Bi et al., 2007; Han et al., 2011; Wang et al., 2008). Re-suspended dust could be from natural sources such as dust storm which occurs often in northern China, or from anthropogenic sources such as road dust, industrial dust (generated during industrial production process), and construction dust. Industrial coal combustion usually refers to soot emitted by large industries like power plants. Previous studies show that dust storm could affect the air quality in China especially for northern cities (Feng et al., 2011; Qu et al., 2010; Wang et al., 2004). Wang et al. (2011a) and Feng et al. (2010) addressed the occurrence of dust storm in China for the past fifty years and found that 80% of dust storms occur in spring (March–May) and seldom occur in autumn. Fig. 5(a) shows the frequency of large dust storm during last decade. 8–20 large dust storms occurred in each year. There is no continuous increasing or decreasing trend, but instead a fluctuation over the past eleven years. Fig. 5(a) also presents the average daily $PM_{10}$ concentration in spring, August and September for the past eleven years. Similar to pollution trend in spring, the concentration is also decreasing year by year in August and September when there is almost no dust storm. However, the decreasing rate in spring is much higher than August and September from 2001 to 2003, which is mainly due to the less frequent dust storm for this period. It is known that wet deposition is the main process for removing $PM_{10}$. As shown in Fig. 5(b), the annual precipitation fluctuated year by year, which cannot be the primary cause of the decreasing $PM_{10}$ concentration in China.

The pollution reduction trend shown by Figs. 3 and 4 is mainly attributed to the change of air pollutant emissions, especially the emission of primary particles (Fig. 5(b)). It is shown that the emissions of dust and soot decreased by 55% and 22%, respectively, from 2001 to 2011. The main control efforts from the Chinese government include a strengthened PM emission standard for

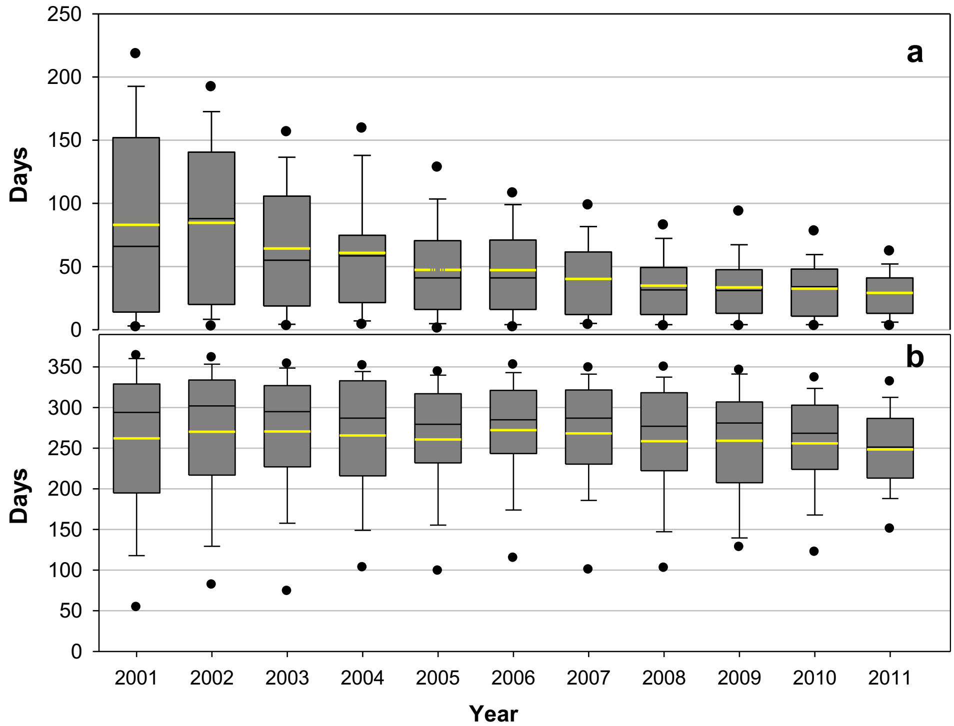


**Fig. 4.** Percentile distribution of all key cities for days with daily concentrations over Class II value of CNAAQS (2012) in (a) and over WHO guideline in (b). The bottom and top of the box represent the 25th and 75th percentile respectively; the black line and yellow line in the box represents the 50th percentile (the median) and mean value; the ends of the whiskers represent the 10th and 90th percentile; and the solid dots represent the 5th and 95th percentile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

power plants issued in 2003, the installation of electrostatic precipitators (ESP) for 92% of the pulverized coal units, and the commercial use of fabric filters for the units with a capacity above 600 MW (Lei et al., 2011; Wang and Hao, 2012). However, the decreasing trend that occurred in 2001–2005 did not match exactly with the change in emissions over the same period. One reason is that fewer dust storms occurred during this period, especially in springs between 2001 and 2003. Another possible reason is the transfer of major pollution sources from urban centers to suburban locations, and from eastern megacities to the central or western province, while most monitoring sites are usually located in urban centers (Lei et al., 2011). It can be seen that the emissions of $SO_2$, an important precursor of sulfate in PM, increased and reached a peak in 2006, then dropped dramatically due to the implement of its emission control policy, while another important precursor, nitrogen oxides ($NO_X$), increased continuously from 2006 because of the lack of strict emission controls. AOD results from satellites such as MODIS and TOMS/OMI showed an increasing trend in eastern China in 2000–2008 (Guo et al., 2011) and 2005–2008 (Lin et al., 2010). Lin et al. (2010) suggested that the different trends between AOD and ground $PM_{10}$ concentrations are due to the rising contribution of secondary fine particles to $PM_{10}$. Though the coarse primary particles are reduced sharply by implementing direct PM abatement controls, their impact on AOD is not as significant as fine particles. Secondary fine particle formation from gaseous precursors such as $NO_X$, ammonia, and volatile organic compounds which currently have modest regulation requirements lead to the increase in AOD (Wang et al., 2011b).

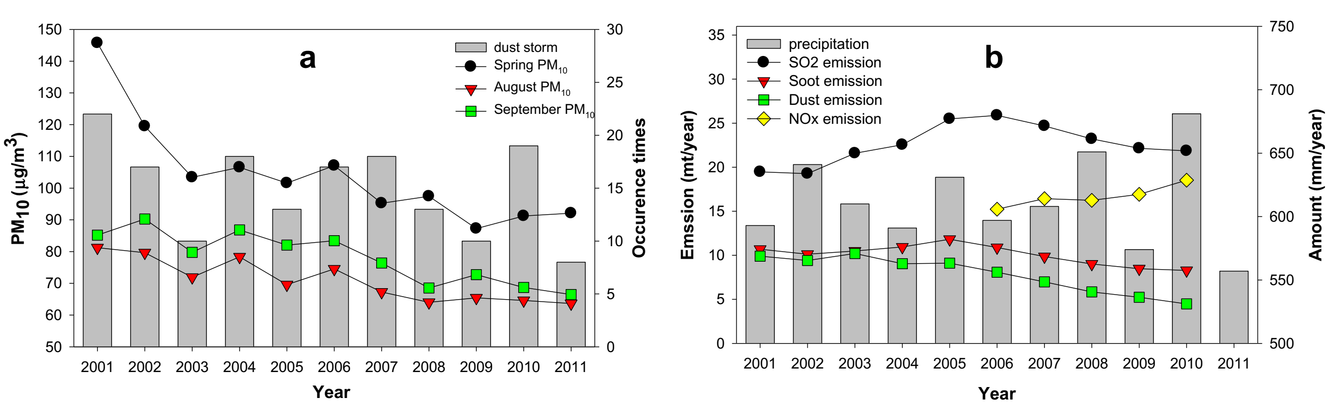


**Fig. 5.** (a) Average $PM_{10}$ daily concentration in spring (March–May), August and September and times of large dust storms for each year. (b) Annual emission of major pollutants in China. Data is from the statistics report of meteorological and environmental bureaus.

### 3.2. Spatial and seasonal distribution

As shown in Fig. 6, the area with high $PM_{10}$ pollution has been reduced notably during last decade. In 2001, the cities with $PM_{10}$ concentration above 130 μg $m^{-3}$ account for 36.2% of national key cities. They mostly locate at northern China. This percentage decreased sharply to 19.1% in 2004 and has become less than 6.0% since 2007. In 2001, the cities with $PM_{10}$ concentration of 100–130 μg $m^{-3}$ account for 21.3% of national key cities. This percentage increased to 31.9% in 2004 because of the shift of cities from high $PM_{10}$ pollution to medium pollution and then kept relatively stable (e.g., 32.5% in 2007). These cities lie in the northwest and the middle of northern China. It further decreased to 15.8% in 2011. The cities with concentration of 70–100 μg $m^{-3}$ account for 19.1% in 2001 and then increased gradually to 60.8% in 2011. The cleanest region with concentration between 40 and 70 μg $m^{-3}$ in the past decade only lies in the south corner and Tibet of China. The decreasing rate of $PM_{10}$ concentration in northern China is much higher than that in southern China because the initial concentration in the north is much higher such that the removal of $PM_{10}$ pollution in the north seems easier and more effective. This experience indicates the difficulties for further reducing $PM_{10}$ pollution in China since more than 80% of key cities have the concentration below 100 μg $m^{-3}$ in 2011.

In 2011, there are still 21 cities whose annual concentration is above 100 μg $m^{-3}$. Ten cities with the highest concentrations are Urumqi (northwest China, 139.3 μg $m^{-3}$), Lanzhou (northwest, 138.3 μg $m^{-3}$), Yan'an (northwest, 121.3 μg $m^{-3}$), Xi'an (northwest, 119.5 μg $m^{-3}$), Chifeng (north, 114.3 μg $m^{-3}$), Hefei (east, 113.4 μg $m^{-3}$), Beijing (north, 112.2 μg $m^{-3}$), Jining (east, 112.0 μg $m^{-3}$), and Luoyang (central, 110.2 μg $m^{-3}$). There are only 27 cities whose annual concentration is below 70 μg $m^{-3}$. The cleanest six cities with concentration below 50 μg $m^{-3}$ lie in the south (Sanya: 24.9 μg $m^{-3}$, Haikou: 40.7 μg $m^{-3}$, Zhanjiang: 43.5 μg $m^{-3}$, Zhongshan: 49.4 μg $m^{-3}$, Zhuhai: 49.7 μg $m^{-3}$) and the southwest (Lhasa, 40.2 μg $m^{-3}$). Most polluted cities are located at northern and western regions, while the cleanest cities are located at south of coastal regions except for Lhasa, a city with very few anthropogenic emissions. These spatial locations are consistent with the result of 2000–2006 reported by Qu et al. (2010), though the average concentration for each city has decreased by approximately 25%.

The reasons for the spatial differences of $PM_{10}$ pollution can be divided into three aspects: emission intensity (Gao et al., 2011; Qu et al., 2010), meteorological conditions especially the removal due to precipitation (Gao et al., 2011; Li et al., 2011; Qu et al., 2010; Wang and Gao, 2008), and the impact of dust storm (Feng et al., 2011; Li et al., 2011; Qu et al., 2010; Wang and Gao, 2008). Most megacities and major industrial sources are located in eastern China, which results in much higher emission intensity than in other regions (Zhang et al., 2009). In addition, the emission increase due to coal burning used for heating in the winter for northern regions is also remarkable (Gao et al., 2011). Both modeling studies (Chate et al., 2003) and field observations (Dong et al., 2007) confirm that it is effective in removing coarse particles like $PM_{10}$ when precipitation occurs. Due to the dominant influence of

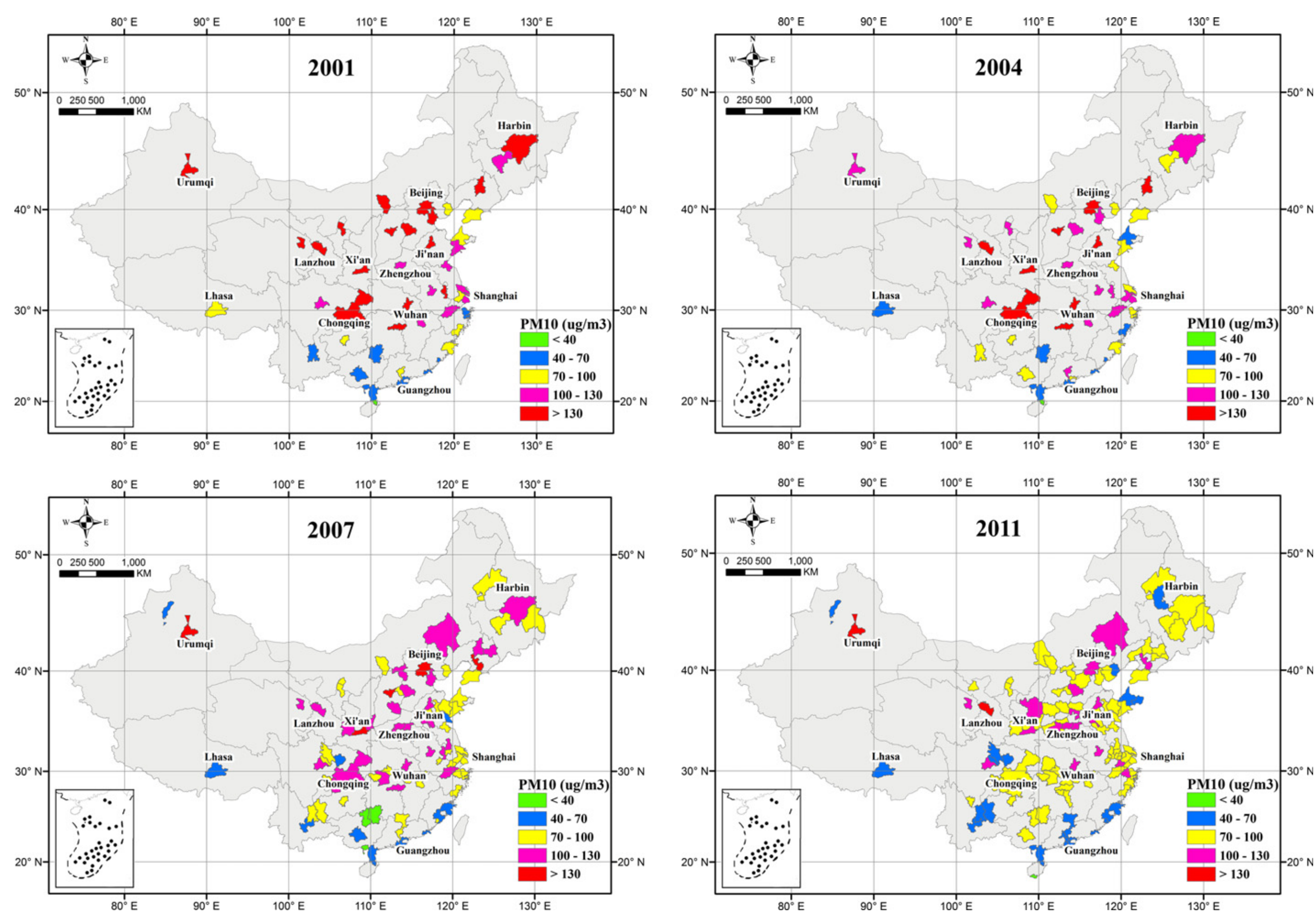


**Fig. 6.** Spatial distribution of annual $PM_{10}$ concentration in China.

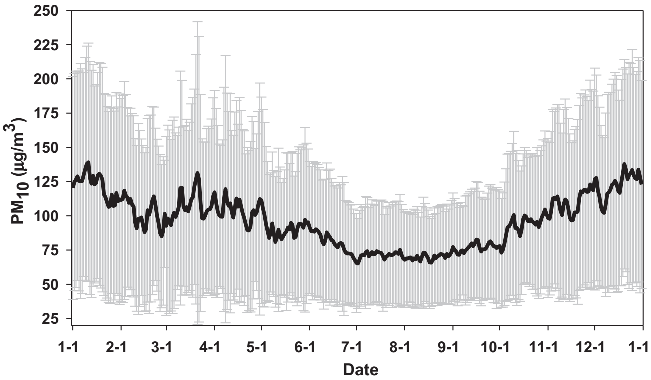


**Fig. 7.** Average daily $PM_{10}$ concentration for all key cities in China (2001–2011). The black line represents the average value, and the ends of the whiskers represent standard deviation.

subtropical oceanic climate, southern areas, especially those coastal cities, have much more precipitation than northern areas, and it is often along with high wind speed and high mixed layer depth which help to lower $PM_{10}$ concentration. As for the dust storms, they originate from northern China, i.e., the desert of Xinjiang or Inner Mongolia Province. This can cause heavy pollution for northern cities in the spring. However, the influence of dust storm on annual average $PM_{10}$ concentration is relatively limited compared to emission and precipitation.

The monthly average concentration for all key cities from 2001 to 2011 is shown in Fig. 7. The average concentrations in 2001–2011 for spring, summer, autumn, and winter are 104.4 μg $m^{-3}$, 75.3 μg $m^{-3}$, 94.7 μg $m^{-3}$, and 118.4 μg $m^{-3}$, respectively. Three most polluted months are December (122.7 μg $m^{-3}$), January (122.0 μg $m^{-3}$), and November (109.4 μg $m^{-3}$), while three cleanest months are August (69.8 μg $m^{-3}$), July (71.4 μg $m^{-3}$), and September (76.9 μg $m^{-3}$). Winter is the most polluted season because of the lack of precipitation (Yu et al., 2012), unfavorable vertical diffusion conditions caused by frequent temperature inversion in most China (Yang et al., 2006; Ye et al., 2008), and increased emission intensity due to coal burning for heating in northern areas. In contrast, summer is the cleanest season because of favorable diffusion conditions especially for coastal cities which are influenced by subtropical oceanic climate (Wang and Gao, 2008). In spring, the strong winds in northern China not only facilitate the formation of dust storm, but also lift the dust in roads and construction sites, which results in spring being the second most polluted season. For autumn, a transition from summer to winter, the concentration is increasing month by month from September to November.

### 3.3. Health impact due to $PM_{10}$ pollution

The rapid urbanization that China has experienced in recent decades has led to a constantly growing population exposed to and affected by $PM_{10}$ pollution (Fig. 8(a), (b)). This factor together with

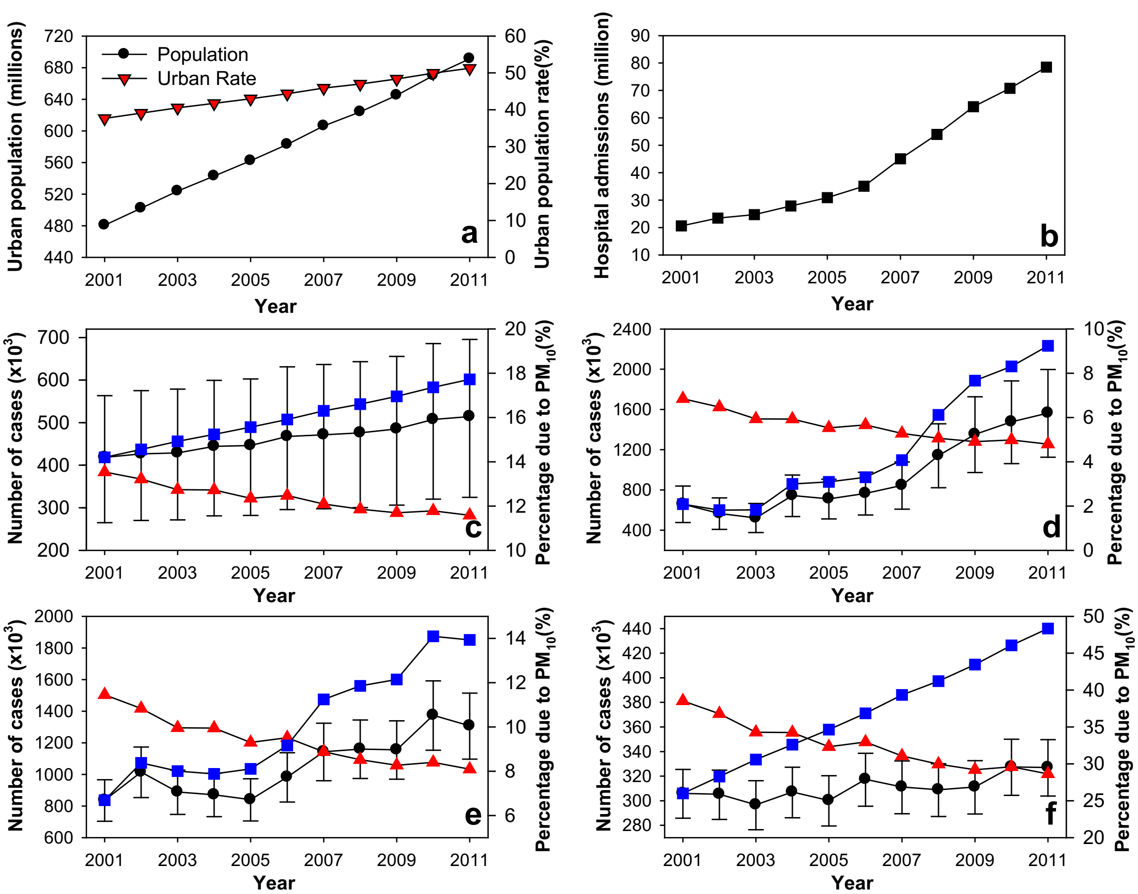


**Fig. 8.** Health outcomes attributable to $PM_{10}$ pollution. (a) Urban population and its ratio to total population in China. (b) Total urban hospital admissions in China. (c) Premature mortality cases due to $PM_{10}$ and its percentage of total cases. (d) Urban cardiovascular hospital admissions due to $PM_{10}$ and its percentage of total cases. (e) Urban respiratory hospital admissions due to $PM_{10}$ and its percentage of total cases. (f) Chronic bronchitis cases due to $PM_{10}$ and its percentage of total cases. For (c)–(f), the black circle and the ends of the whiskers represent the best estimate, lower limit CL and upper limit CL respectively, while the red triangle represents the attributable fraction (AFs) for each endpoint, the blue square represents the best estimate assumed $PM_{10}$ concentration stays constant from 2001. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$PM_{10}$ pollution reduction has direct influences on those estimations of the burden of particulate matter on human health in urban China.

The total number of premature deaths has been constantly increasing from 418,000 cases in 2001 to approximately 514,000 cases in 2011 (Fig. 8(c)): these numbers are slightly lower than the 470,000 premature deaths for the year 2000 reported in Zhang et al. (2010) but higher than the 394,000 reported in World Bank (2007). In 2001 the premature deaths attributable to $PM_{10}$ amounts for 13.5% of the all causes of deaths in urban areas of China while in 2011 this figure was reduced to 11.6% in parallel with the reduction in $PM_{10}$ concentration. If compared with the hypothetical case where $PM_{10}$ remains constant since 2001 with no pollution control, a best estimate total of 511,000 premature deaths were avoided due to $PM_{10}$ concentration reduction.

The number of cardiovascular hospital admissions increased from 659,000 to 1,565,000, while the percentage decreased from 6.85% to 4.80% (Fig. 8(d)). A similar trend was found for respiratory hospital admissions. The absolute cases increased from 836,000 to 1,307,000 while the percentage decreased from 11.46% to 8.09% (Fig. 8(e)). This might be due to the sharp increase of hospital admissions for all reasons and the continuous augment of urban population in the same period. The total avoided cases of cardiovascular and respiratory hospital admissions are 2,967,000 and 2,938,000, respectively, for last decade under best estimate. From Fig. 8(f), the absolute number of chronic bronchitis cases is approximately 310,000 yearly in last decade while the percentage decreased from 38.5% to 28.6% with the reduction of $PM_{10}$ concentration. Some 676,000 cases in total as best estimation could have been benefited in last decade as a result of $PM_{10}$ pollution control.

## 4. Conclusions

Long-term trends, spatial and seasonal distribution, and health impacts of particulate matter pollution in China are evaluated based on daily $PM_{10}$ concentration in different cities during the last decade. The annual average $PM_{10}$ concentration decreased significantly from 2001 to 2011, i.e., from 116.4 to 85.3 $\mu g\ m^{-3}$. The number of polluted days above Chinese new ambient air quality standard for the 50th percentile cities decreased from 66 in 2001 to 28 in 2011, though there is still a significant number of days over WHO guideline value. It is shown that $PM_{10}$ reduction is mainly attributed to the change of pollutant emissions, especially the emission of primary coarse particles. The most polluted areas with annual $PM_{10}$ concentration above 100 $\mu g\ m^{-3}$ mainly lie in northern China although they have been improved notably during the last decade. The cleanest region of below 50 $\mu g\ m^{-3}$ lies in the southern fringe of China and has remained stable during the past eleven years. The variation of emission intensity, meteorological conditions, precipitation, and dust storm at different locations in China accounts for the observed spatial difference. Similarly, the lack of precipitation, unfavorable diffusion conditions, and/or emission intensity increased by winter heating lead to winter being the most polluted season. Great benefit on public health has been achieved as a result of $PM_{10}$ concentration reduction. The impact fraction of $PM_{10}$ with respect to all causes for four health endpoints, i.e., premature mortality, cardiovascular and respiratory hospital admissions, and chronic bronchitis decreased and a large number of cases was avoided due to $PM_{10}$ reduction in the last decade. However, the absolute number of four health endpoints increased from 2001 to 2011 due to the increasing urban population that was exposed to air pollution. Particulate matter control should be strengthened in the future, especially the control of fine particles which pose greater risk to public health and their gaseous precursors.

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