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Health burden attributable to ambient $PM_{2.5}$ in China☆

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A B S T R A C T

In China, over 1.3 billion people have high health risks associated with exposure to ambient fine particulate matter ($PM_{2.5}$) that exceeds the World Health Organization (WHO) Air Quality Guidelines (AQG). The $PM_{2.5}$ mass concentrations from 1382 national air quality monitoring stations in 367 cities, between January 2014 and December 2016, were analyzed to estimate the health burden attributable to ambient $PM_{2.5}$ across China. The integrated exposure-response model was applied to estimate the relative risks of disease-specific mortality. Disease-specific mortality baselines in province-level administrative units were adjusted by the national mortality baseline to better reveal the spatial inequality of the health burden associated with $PM_{2.5}$. Our study suggested that $PM_{2.5}$ in 2015 contributed as much as 40.3% to total stroke deaths, 33.1% to acute lower respiratory infection (ALRI, <5yr) deaths, 26.8% to ischemic heart disease (IHD) deaths, 23.9% to lung cancer (LC) deaths, 18.7% to chronic obstructive pulmonary disease (COPD) deaths, 30.2% to total deaths combining IHD, stroke, COPD, and LC, 15.5% to all cause deaths. The population weighted average (PWA) attributable mortality rates (10^{-5} y^{-1}) were 112.0 in current year analysis, and 124.3 in 10-year time lag analysis. The Mortality attributable to $PM_{2.5}$ in 10-year time lag analysis (1.7 million) was 12% higher than the current year analysis (1.5 million). Our study also estimated site-specific annual $PM_{2.5}$ concentrations in scenarios of achieving WHO interim targets (ITs) and AQG. The mortality benefits will be 24.0%, 44.8%, 70.8%, and 85.2% of the total current mortalities (1.5 million) when the PWA $PM_{2.5}$ concentrations in China meets the WHO IT-1, IT-2, IT-3, and AQG, respectively. We expect air quality modeling and cost-benefits analysis of emission reduction scenarios and corresponding health benefits in meeting the site-specific annual $PM_{2.5}$ concentrations (WHO IT-1, IT-2, IT-3, and AQG) this study raised.

1. Introduction

Ambient fine particulate matter ($PM_{2.5}$) pollution ranked the 6th among all of the risk factors for global premature mortalities and disability-adjusted life-years (DALYs), and it contributed to 4.24 million deaths and 103.1 million DALYs in the Global Burden of Diseases (GBD) project 2015 (Forouzanfar et al., 2015, 2016). Long-term exposure to high concentrations of $PM_{2.5}$ was associated with serious health impacts by stroke, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer (LC) and acute lower respiratory infection (ALRI) (Arnold, 2014; Burnett et al., 2014; Dockery et al., 1993; Lelieveld et al., 2015; Li et al., 2016a; Lim et al., 2012; Lin et al., 2016; Pope et al., 2011).

Chinese cohort studies also showed that long-term exposure to $PM_{2.5}$ was associated with an increased risk of mortalities. In a long-term (1991–2000) cohort study in 71,000 residents of 31 Chinese cities (Burnett et al., 2014; Cao et al., 2011), increases of 2.1%, 3.3% and 3.3% in IHD, stroke, and LC mortality, respectively, were associated with a 10 μg m^{-3} change in estimated equivalent

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$PM_{2.5}$. In a 12-year (1998–2009) cohort study in Northern China, each 10 μg m^{-3} increase in PM_{10} concentrations was associated with a 4.7% increase in LC mortality in the time-varying exposure model, a 8.7% increase in the baseline exposure model (Chen et al., 2016), 23%, 23%, 37% and 24% increases in the mortality from cardiovascular, cerebrovascular, IHD and all-cause mortality, respectively (Zhang et al., 2014). In a 15-year (1990–2005) follow-up study from 44 counties or cities in China, an increase in $PM_{2.5}$ of 10 μg m^{-3} was associated with a 9.7%, 4.4%, 13.5% increases in the risks of mortality from IHD, hemorrhagic stroke, and ischemic stroke, respectively (Yin et al., 2015). An increase in PM_{10} of 10 μg m^{-3} corresponded to 23–67% increase in the risks of mortality in terms of long-term effects, according to meta-analysis review (Lu et al., 2015; Shang et al., 2013). The conversion of PM_{10} to $PM_{2.5}$ could empirically refer to the average ratios of $PM_{2.5}$ to PM_{10} in China, which was 0.62 in urban areas and 0.60 in suburban areas (Zhou et al., 2016b).

In GBD 2015 study, Stroke, IHD, LC and COPD were the 1st, 2nd, 4th, and 5th leading causes of deaths in China, respectively (Forouzanfar et al., 2016). The total deaths caused by IHD, stroke, COPD, and LC accounted for almost 51.4% of the all cause deaths in China 2015 (Wang et al., 2016b). Air pollution was responsible for 21% of all cardiovascular deaths, 25% of IHD deaths, 24% of stroke deaths, and 27% of LC deaths (Landrigan, 2016; Wang et al., 2016b). Additionally, China is one of the most polluted countries, with nearly none of the population living in areas meeting the World Health Organization (WHO) Air Quality Guidelines (AQG) of 10 μg m^{-3} (Apte et al., 2015; Ma et al., 2015; van Donkelaar et al., 2010; Van Donkelaar et al., 2015; West et al., 2016), suggesting that China's leading mortality causes (stroke, IHD, LC and COPD) could be attributed to $PM_{2.5}$ exposure to some extent (Cao et al., 2011; Guan et al., 2016; Yang et al., 2013; Yin et al., 2015).

The uncertainty in the mortality effects assessment of ambient $PM_{2.5}$ often lies in the exposure assessment and mortality baseline. $PM_{2.5}$ was added into Chinese Ambient Air Quality Standard (CAAQS) in 2012. The Ministry of Environmental Protection (MEP) of China started to open the access of $PM_{2.5}$ data at each national air quality monitoring site (NAQMS) of some major cities through the official website since January 2013 (Wang et al., 2014b; Zhang and Cao, 2015; Zhao et al., 2016). To date, ground-based air quality monitoring networks of mainland China were comprised of 1382 monitoring stations in 367 cities, which were almost twice as the number of cities (190) in 2013. The intensive ground-based monitoring networks made it possible to obtain insights into the real-data driven spatial variation of $PM_{2.5}$ mass concentrations across China. In this study, Chinese province-level mortality rates of deaths for IHD, stroke, COPD and LC in 2013 from the GBD 2013 (Zhou et al., 2016a) study (Fig. S1) were adjusted by GBD 2015 database to derive province-level mortality data in 2015.

The mortality effects assessment of ambient $PM_{2.5}$ at global or national level has been studied (Apte et al., 2015; Brauer et al., 2012; Chen et al., 2017; Fang et al., 2016; Lelieveld et al., 2013, 2015; Liu et al., 2016; Liu et al., 2017; Xie et al., 2016a). Previous studies reported relatively accurate mortality effects at national level, but few studies at subnational or site-specific level of health burden attributable to $PM_{2.5}$ especially the spatial variations of disease-specific mortality rates (10^{-5} y^{-1}) associated with $PM_{2.5}$, and province-level health benefits (Li et al., 2016c) of meeting WHO interim targets have been reported.

Recently, a growing evidence revealed that shot-term exposure to various chemical constituents of $PM_{2.5}$ was associated with adverse health effects (Bell et al., 2009; Cao et al., 2012; Ito et al., 2011; Kim et al., 2012; Ostro et al., 2010; Philip et al., 2014; Son et al., 2012; Zhou et al., 2011). To date, long-term exposure to $PM_{2.5}$ chemical components are less well understood and need to study further (Lepeule et al., 2012; Philip et al., 2014).

In this study, $PM_{2.5}$ data from NAQMS and scenarios of meeting WHO standards, population census data, and provincial mortality baselines were integrated to complete health burden of ambient $PM_{2.5}$ across China. The chemical compositions and source apportionments of $PM_{2.5}$ in Chinese cities were also reviewed and summarized according to published data before 2016.

2. Materials and methods

2.1. Data

2.1.1. Ground monitoring $PM_{2.5}$

Validated real-time hourly concentrations of $PM_{2.5}$ from January 2014 to December 2016 in all Chinese cities were downloaded from the website of the China National Environmental Monitoring Center (http://113.108.142.147:20035/emcpublish/). The quality assurance and controls of state controlled monitoring data were reported in previous studies (Wang et al., 2014b; Zhao et al., 2016).

All of the downloaded data were pre-processed to reject spatial and temporal outliers. This was carried out by comparing every single concentration with its adjacent monitoring stations and with the time series data. Our removal criterion consisted of four conditions, of which three conditions were in consistent with previous research (Barrero et al., 2015). First, the series data were transformed into z scores (i.e. standard score). The points in the transformed time series meeting the conditions (1) having an absolute z score larger than 4 ($|z_t| > 4$), (2) the increment from the previous value being larger than 9 (z_t-z_{t-1}>9), (3) the ratio of the value to its centered rolling mean of order 3 (RM3) being larger than 2 (z_t/RM3(z_t) > 2), and (4) individual monitoring station's increment from the previous value being two times larger than belonged city's all monitoring station's averaged increment (city(z_t-z_{t-1})) from the previous value (i.e., (z_t-z_{t-1})/city(z_t-z_{t-1})>2), were then removed from the hourly raw data. The missing data were filled with the time-interpolated method. The daily city-level pollution was represented by the daily average pollutant concentrations of all the monitoring stations within this city (Li et al., 2016b).

2.1.2. Population data

The population data in this study was downloaded from the website of the National Bureau of Statistics of the People's Republic of China (http://www.stats.gov.cn/ztjc/zdtjgz/zgrkpc/dlcrkpc/). The latest census data were from the Sixth National Population Census carried out in 2010. Although some cities might have released their new version of population data updated after 2010, we still used the population data from the Sixth National Population Census to ensure data integrity and consistency, considering a few small cities did not have relatively correct population data since 2010. The resolution of the census data was on a county-level, which could be summed up to city-level for our study purpose.

2.1.3. Mortality baseline

Cause-specific mortality data of China in 2015 were obtained from GBD 2015 database (Wang et al., 2016b). Province-level mortalities in 2013 from the GBD 2013 study (Zhou et al., 2016a) (Fig. S1) were adjusted by GBD 2015 database to derive province-level mortality data in 2015. The causes of mortality were defined by the International Classification of Diseases 10 (ICD-10) code: IHD (I20-I25); stroke (I60-I67, I69.0, I69.1, I69.2, I69.3); lung cancer (C33, C34); COPD (J40-J44); and ALRI (J09-J15.8, J16-J16.9, J20-J21.9, P23-P23.9).

2.2. Methods

2.2.1. Health impact estimation

Health end points associated with $PM_{2.5}$ exposure could be categorized into morbidity and chronic mortality. For chronic mortality relative risk, we adopted the global IER model (Table S1 and Fig. S2) (Burnett et al., 2014) with the counterfactual concentration of $PM_{2.5}$ (where RR = 1) in the range of 5.8–8.8 μg m^{-3}. For morbidity excess risk, we adopted the linear exposure-response functions (Table S2) (Xie et al., 2016b).

The attributable fraction (AF) measures the contribution of a risk factor to disease or mortality (Ezzati et al., 2003). The following model was used to estimate the disease-specific AF associated with exposure to ambient $PM_{2.5}$ (Anenberg et al., 2010; Lelieveld et al., 2013):

$$AF_{i,j} = \frac{RR_{C_i,j} - 1}{RR_{C_i,j}} \tag{1}$$

where C_i is the annual mass concentration of $PM_{2.5}$ at site i, and $RR_{C_i,j}$ is the relative risk for disease j at exposure level C_i calculated from IER functions.

The attributable mortality rates (AMR) of total deaths combining IHD, stroke, COPD and LC were estimated as follows:

$$AMR_i = \sum_{j=1}^{n} \left(AF_{i,j} \times y_{i,j}\right) \tag{2}$$

where $y_{i,j}$ is the mortality rate for disease j at site i.

The AF of total deaths caused by IHD, stroke, COPD and LC were estimated as follows:

$$AF_i = \frac{AMR_i}{\sum_{j=1}^{n} y_{i,j}} \tag{3}$$

To evaluate the health benefits (HB) of population-weighted average (PWA) $PM_{2.5}$ mass concentrations in China meeting the WHO interim targets (IT1, IT2 and IT3) and AQG, we used:

$$\text{For mortality,} \quad HB_i = Pop_i \times \sum_{j=1}^{n} \left(\frac{RR_{C_i,j} - RR_{Ref,j}}{RR_{C_i,j}} \times y_{i,j}\right) \tag{4}$$

$$\text{For morbidity,} \quad HB_i = Pop_i \times \sum_{j=1}^{n} \left(ERF_j \times \left(C_i - C_{Ref}\right)\right) \tag{5}$$

where *Pop*, *ERF* are the exposed population number and exposure-response functions. The suffixes *i, j, Ref* represent different cities *i*, different health endpoints *j* (for chronic mortality, they are IHD, stroke, COPD and LC, for morbidity, they are work loss days and morbidity cases of respiratory, cerebrovascular and cardiovascular hospital admission, chronic bronchitis, asthma attacks, respiratory symptom days), and reference concentrations (IT1: 35 μg m^{-3}, IT2: 25 μg m^{-3}, IT3: 15 μg m^{-3} and AQG: 10 μg m^{-3}). The health benefits (HB) are equal to attributable mortalities (AM) when the reference concentrations are the counterfactual concentration of $PM_{2.5}$ (where RR = 1).

2.2.2. Reference scenario

To estimate the $PM_{2.5}$ mass concentrations at each NAQMS in different scenarios (year 2005 which is the 10-y time lag for this study, WHO IT1, IT2, IT3 and AQG), the annual $PM_{2.5}$ standard scores (z-scores) at each NAQMS in 2015 were utilized to adjust the national annual $PM_{2.5}$ concentrations (2005: 68.6 μg m^{-3} (Kan et al., 2012; Liu et al., 2017), IT1: 35 μg m^{-3}, IT2: 25 μg m^{-3}, IT3: 15 μg m^{-3}, AQG: 10 μg m^{-3}) to derive site-specific $PM_{2.5}$ concentrations.

2.2.3. Statistical analysis

We used a logistic regression to fit the city-level $PM_{2.5}$ mass concentration (x), and AF (x) with an associated cumulative exposed population percentage (F(x)). The regression is defined as follows:

$$F(x) = \frac{1}{1 + \left(\frac{x}{x_0}\right)^p} \tag{6}$$

where: p = Hill's slope. The Hill's slope refers to the steepness of the curve and its dispersion or spread. x_0 = Inflection point, and the inflection point is defined as the point on the curve where the curvature changes direction. x_0 is the exposed data that is covering 50% of the total population.

2.2.4. Uncertainty analysis

95% confidential intervals (CI) of attributable mortalities (AM) were given in this study. The average, 2.5%, and 97.5% cause-specific RR values under certain $PM_{2.5}$ exposure concentration were given by Burnett et al. (2014). The fit parameters for the IER model were presented in Table S1. Considering the lag health effects of long-term $PM_{2.5}$ exposure, we also conducted a 10-year time lag analysis using the $PM_{2.5}$ concentration in 2005 and the mortality data in 2015.

3. Results

3.1. $PM_{2.5}$ exposure assessment

Fig. 1 (a) shows the spatial distribution of annual $PM_{2.5}$ mass concentrations (μg m^{-3}) at NAQMS in 2014, 2015 and 2016. The annual mass concentrations of ground $PM_{2.5}$ showed a significant geographic variation across China (from 17 μg m^{-3} to 143 μg m^{-3} in 2014, from 10 μg m^{-3} to 131 μg m^{-3} in 2015, from 8 μg m^{-3} to 146 μg m^{-3} in 2016). The spatial patterns of annual $PM_{2.5}$ mass concentrations in China remained steady during this study periods. As illustrated in Fig. 1 (a), the regions with highest $PM_{2.5}$ concentration were located in the Northern China Plain, the Middle-Lower Yangtze Plains, the Sichuan Basin and Tarim Basin. The Z-scores (Fig. S3) in 2015 showed a good agreement with those in 2014 (n = 881, R^2 = 0.83) and 2016 (n = 1494, R^2 = 0.82) (as shown in Fig. 1 (b)), suggesting that the spatial inequalities caused by the $PM_{2.5}$ pollution remain steady recent years. Assuming the generally spatial-differentiation of $PM_{2.5}$ pollution were not significantly altered, the z-scores of NAQMS in 2015 could be utilized to adjust the national annual $PM_{2.5}$ reference concentrations of different scenarios (year 2005 which is the 10-y time lag for this study: 68.6 μg m^{-3} (Kan et al., 2012; Liu et al., 2017), WHO IT1: 35 μg m^{-3}, IT2: 25 μg m^{-3}, IT3: 15 μg m^{-3}, AQG: 10 μg m^{-3}) to estimate corresponding site-specific annual $PM_{2.5}$ mass concentrations. The density distributions of annual $PM_{2.5}$ concentrations at each NAQMS of different reference scenarios are displayed in Fig. 2. $PM_{2.5}$ pollution in China showed significant declines especially from 2014 (62.8 μg m^{-3}) to 2016 (48.1 μg m^{-3}). The spreads of the $PM_{2.5}$ concentrations suggested that China still has a long way to go especially for those cities with annual $PM_{2.5}$ concentration higher than 50 μg m^{-3} if China aims to achieve WHO IT1 (or CAAQS II standard), IT2, IT3 and AQG standards.

From the logistic population regression (Fig. 3), 50% population in China were exposed to annual $PM_{2.5}$ mass concentration with

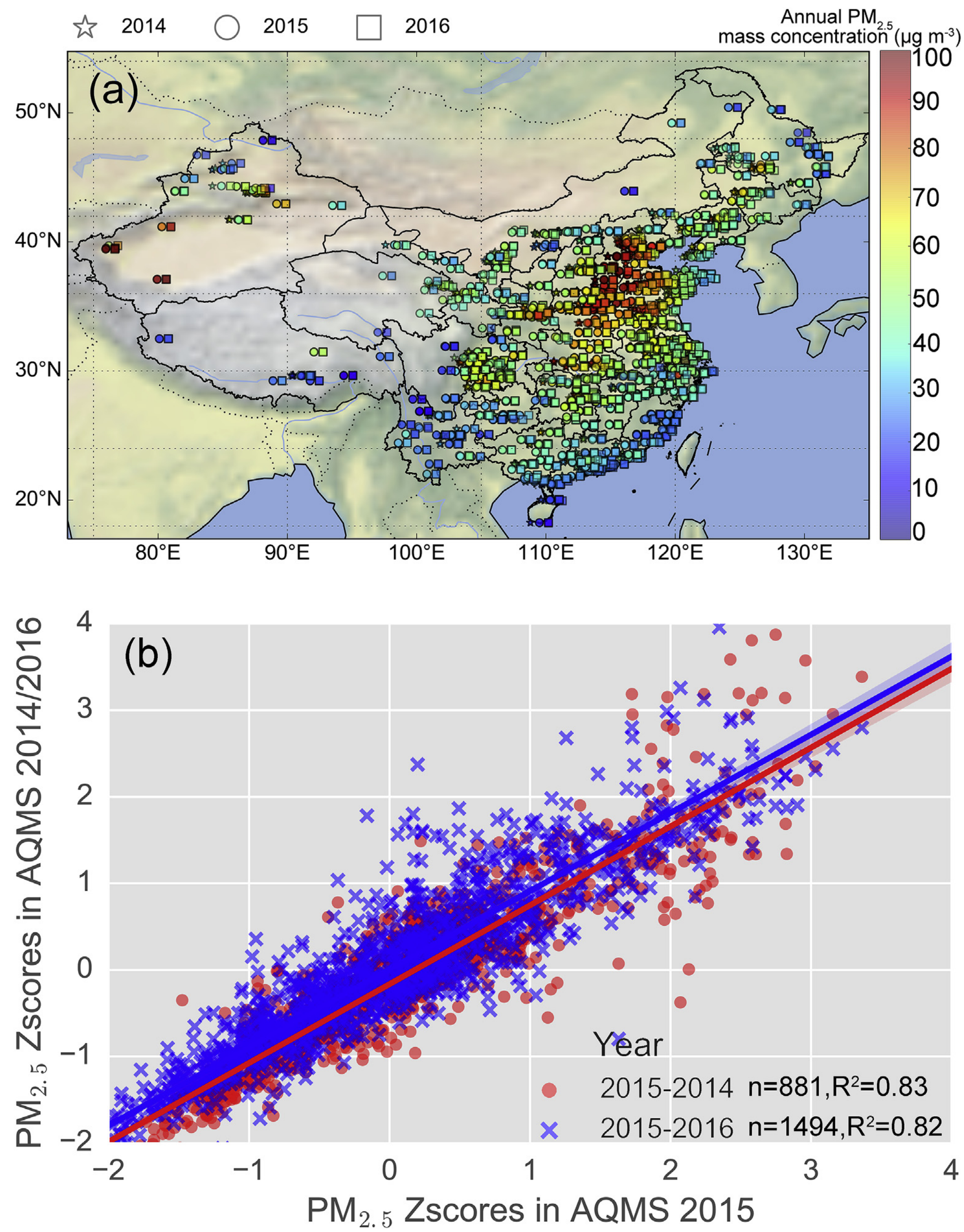

Fig. 1. Spatial distribution of annual $PM_{2.5}$ mass concentration (a) and correlations of $PM_{2.5}$ z-scores (b) from NAQMS in 2014, 2015 and 2016 (the longitude of NAQMS in 2014 and 2016 were shifted to left side ($-0.7°$) and right side ($+0.7°$) of those in 2015, respectively).

63.7 μg m^{-3} in 2014, 53.0 μg m^{-3} in 2015 and 48.2 μg m^{-3} in 2016. In China, 95%, 87% and 81% population were exposed to $PM_{2.5}$ concentrations higher than WHO IT1 (or CAAQS) standard in 2014, 2015 and 2016, respectively. None of the population of China lived in areas meeting the WHO guideline of 10 μg m^{-3} during this study period.

$PM_{2.5}$ concentration in Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD), Pearl River Delta (PRD) and Sichuan-Chongqing (CY) city clusters all showed significant declines from 2014 to 2016. However, the entire population living in the four city clusters was still exposed to $PM_{2.5}$ concentrations above WHO IT2, IT3 and AQG. The citizens living in the BTH city cluster were exposed to the highest $PM_{2.5}$ concentration, with 91% (2014), 86% (2015) and 73% (2016) of the city-cluster's population exceeding 70 μg m^{-3} (twice as much as the CAAQS of China). The PRD had the lowest annual $PM_{2.5}$ concentrations with nearly half population in PRD were exposed to $PM_{2.5}$ concentrations meeting WHO IT1 (or CAAQS) standard.

3.2. Mortality attributable to $PM_{2.5}$

City-level AFs of disease-specific mortality was estimated by applying IER functions to city-level annual $PM_{2.5}$ mass concentrations. Fig. 4 illustrates the disease-specific AFs in China in 2005, 2014–2016, and scenarios of meeting WHO interim targets (IT1, IT2, and IT3).

In 2015, the city-level AF (%) varied from 10.4 (2014: 17.1, 2016: 9.5) to 34.0 (34.7, 36.0) for IHD, 4.1 (17.9, 4.9) to 49.5 (49.7, 50.0) for stroke, 3.9 (8.4, 9.5) to 29.7 (31.0, 33.8) for COPD, 4.5 (10.4, 4.2) to 37.8 (39.4, 42.7) for LC, and 2.3 (9.7, 2.6) to 53.7 (55.4, 58.3) for ALRI.

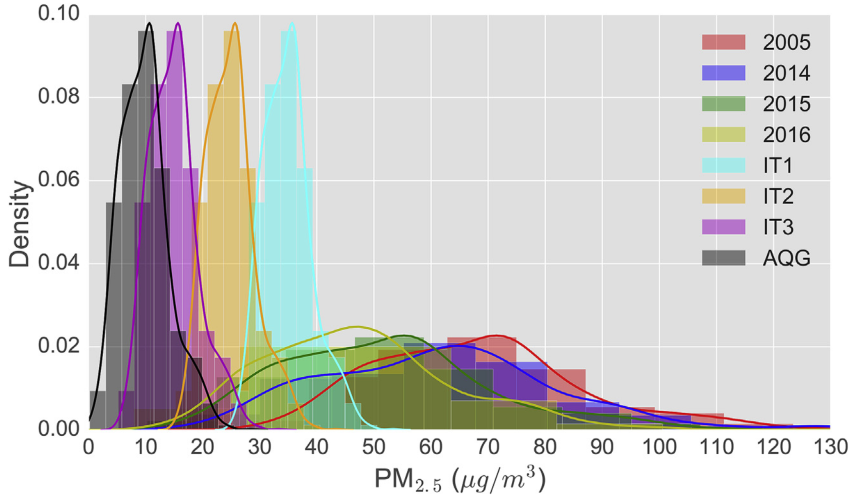

Fig. 2. Density plots of site-specific annual $PM_{2.5}$ in different scenarios. Lines represent smooth fit of density function.

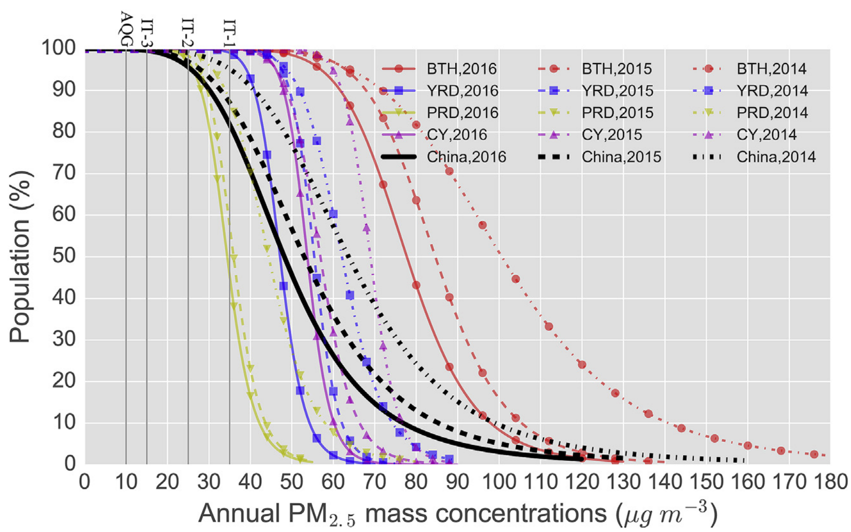

Fig. 3. Population exposure to $PM_{2.5}$ in four megacity clusters and China (the vertical ordinate is cumulative distribution of population percentage over the range of $PM_{2.5}$ concentrations in the areas where the residents lived).

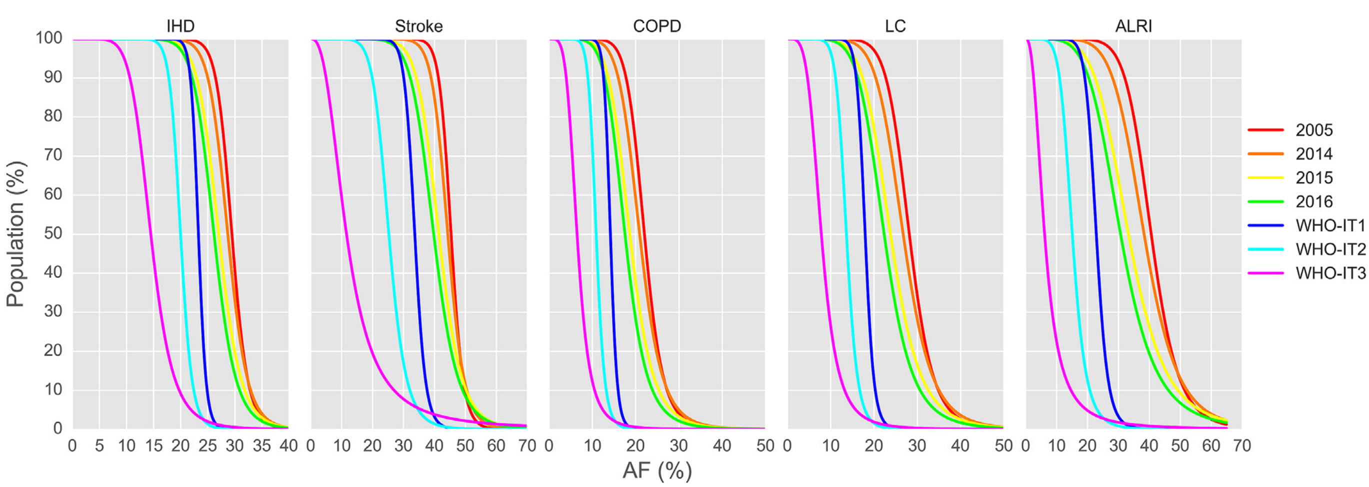

Fig. 4. Population exposure of disease-specific AFs in 2005, 2014–2016, and WHO interim targets.

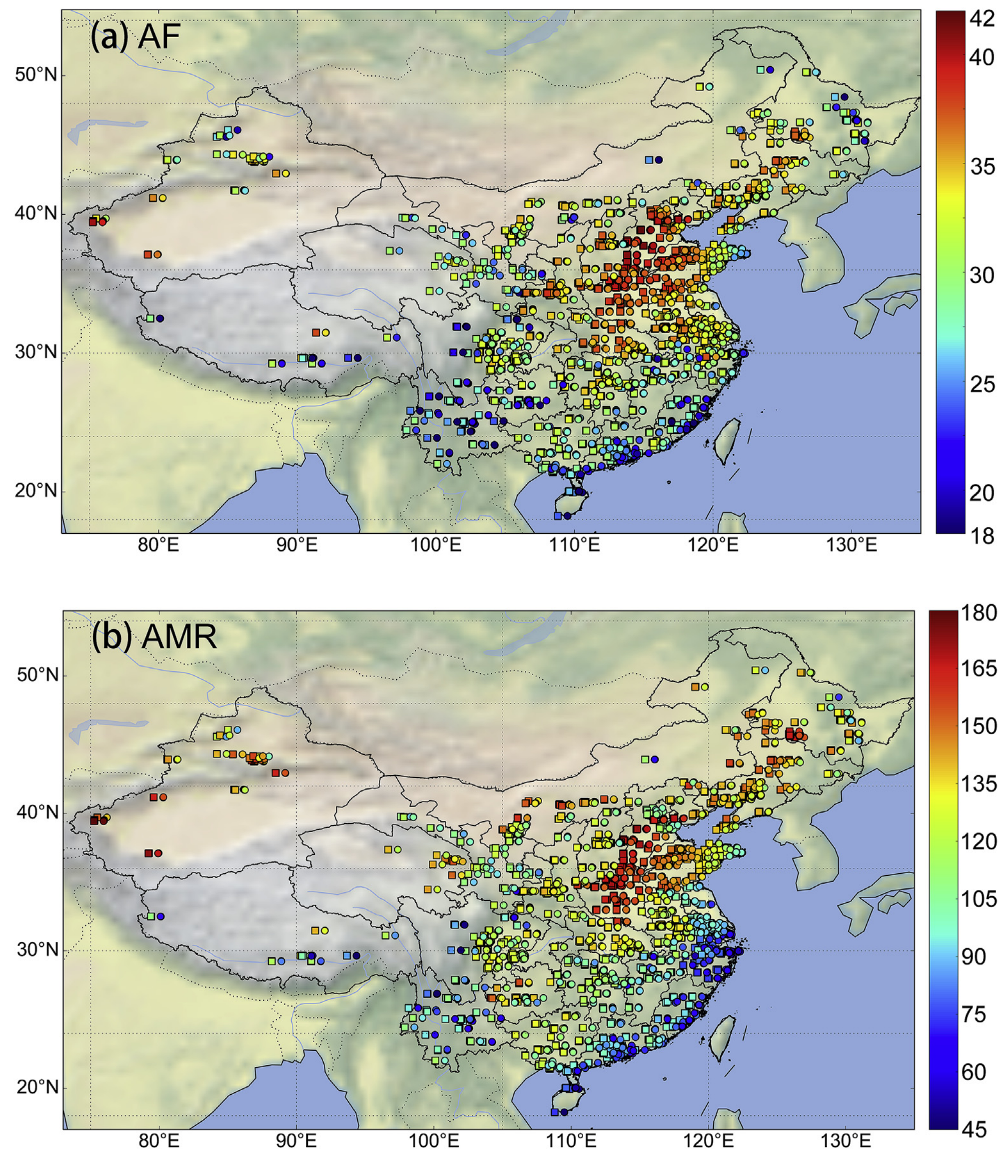

Fig. 5. Attributable fractions (%) (a) and attributable mortality rates (10^{-5} y^{-1}) (b) combining IHD, stroke, LC, and COPD in 2015. (Circle for the main analysis, square for the 10-year time lag analysis, the offset of longitude on the map is 0.7°).

In a previous global study (Burnett et al., 2014), the percent AF exposure varied among countries from 2 to 41 for IHD, 1 to 43 for stroke, <1 to 21 for COPD, <1 to 25 for LC, and <1 to 38 for ALRI. AF exposure (Fig. S4) in China showed a so called global trend because of the spatial heterogeneity of pollutant emissions and topographic features.

Ambient $PM_{2.5}$ contributed as much as 40.3% (95%CI: 14.1%, 52.2%) to total stroke deaths, 33.1% (95%CI: 22.6%, 42.4%) to total ALRI (<5yr) deaths, 26.8% (95%CI: 18.6%, 41.3%) to total IHD deaths, 23.9% (95%CI: 7.7%, 33.7%) to total LC, and 18.7% (95%CI: 9.1%, 27.4%) to total COPD deaths in China. AFs exposure in China showed a significant declines especially during this study period. However, there are still a lot of room for potential declines of AF if China continues to improve ambient air quality to meet the WHO IT-1, IT2, IT3 and AQG standards (Fig. 4).

Based on the disease-specific mortality in China in the year 2015, we estimated the mortality burden attributable to current ambient $PM_{2.5}$ exposure. Considering the lagged health effects of long-term $PM_{2.5}$ exposure, we also conducted a 10-year time lag analysis using the $PM_{2.5}$ concentration in 2005 and the mortality data in 2015. Fig. 5 shows spatial distribution of AF (%) and AMR (10^{-5} y^{-1}) of total deaths caused by IHD, stroke, COPD and LC in 2015 and 2005. The PWA AF (%) of total deaths caused by IHD, stroke, COPD and LC in China were 30.2 (95% CI: 13.9, 42.4) in 2015, 34.1 (95% CI: 15.9, 46.2) in 2005. The PWA AMR (10^{-5} y^{-1}) were 112.0 (95% CI: 50.7, 154.6) in current year analysis, 124.3 (95% CI: 58.1, 168.4) in 10-year time lag analysis. Generally, the attributable fraction and number of deaths from $PM_{2.5}$ in 10-year time lag analysis was 12% higher than the current year analysis. Mortality numbers attributable to $PM_{2.5}$ in Chinese provincial level were presented in Table 1. Detailed province-level attributable fractions (%) and attributable mortality rates (10^{-5} y^{-1}) were illustrated in Table S5.

3.3. Health benefits from meeting WHO $PM_{2.5}$ standards

The potential mortality rates (10^{-5} y^{-1}) benefits in scenarios where the annual $PM_{2.5}$ mass concentrations in China meet the

Table 1
Health burden attributable to $PM_{2.5}$ in 2015 and health benefits of annual $PM_{2.5}$ concentrations in China meeting the WHO standards.

Province	Population ($\times10^6$)	2015			IT1				IT2				IT3				AQG			
		$PM_{2.5}$ (μg m^{-3})	Attributable deaths ($\times10^3$)		$PM_{2.5}$ (μg m^{-3})	benefits			$PM_{2.5}$ (μg m^{-3})	benefits			$PM_{2.5}$ (μg m^{-3})	benefits			$PM_{2.5}$ (μg m^{-3})	benefits		
			Main analysis	10-y time lag		Deaths ($\times10^3$)	Work loss day ($\times10^6$)	Morbidity cases ($\times10^6$)		Deaths ($\times10^3$)	Work loss day ($\times10^6$)	Morbidity cases ($\times10^6$)		Deaths ($\times10^3$)	Work loss day ($\times10^6$)	Morbidity cases ($\times10^6$)		Deaths ($\times10^3$)	Work loss day ($\times10^6$)	Morbidity cases ($\times10^6$)
Hebei	71.9	83.9	111.2	117.0	42.3	34.1	61.9	75.3	32.3	50.0	76.8	93.4	22.3	70.0	91.7	111.5	17.3	81.7	99.1	120.6
Henan	93.4	80.6	145.9	153.0	41.5	47.3	75.4	91.8	31.5	67.7	94.7	115.3	21.5	93.4	114.1	138.8	16.5	108.5	123.7	150.6
Beijing	19.6	80.5	20.9	21.9	41.5	6.7	15.8	19.3	31.5	9.5	19.9	24.2	21.5	13.1	23.9	29.1	16.5	15.2	26.0	31.6
Xinjiang	18.0	77.3	27.1	29.1	40.8	7.9	13.6	16.5	30.8	12.0	17.3	21.1	20.8	17.2	21.0	25.6	15.8	20.3	22.9	27.8
Shandong	106.9	74.5	147.0	156.8	40.1	45.0	76.0	92.5	30.1	67.5	98.1	119.4	20.1	95.6	120.3	146.4	15.1	112.7	131.3	159.8
Tianjin	12.9	69.9	13.6	14.5	39.1	4.2	8.3	10.0	29.1	6.2	10.9	13.3	19.1	8.8	13.6	16.6	14.1	10.4	14.9	18.2
Hubei	56.9	65.9	71.2	76.5	38.1	21.9	32.6	39.7	28.1	34.0	44.4	54.1	18.1	48.9	56.2	68.4	13.1	57.8	62.1	75.6
Jiangsu	91.4	57.8	85.3	93.4	36.3	24.7	40.8	49.6	26.3	40.9	59.7	72.7	16.3	61.0	78.6	95.7	11.3	72.9	88.1	107.2
Jiangxi	35.7	57.3	42.7	46.7	36.1	11.7	15.6	19.0	26.1	19.9	23.0	28.0	16.1	30.2	30.4	37.0	11.1	36.4	34.1	41.5
Anhui	55.6	57.2	66.4	72.9	36.1	18.6	24.2	29.5	26.1	31.5	35.8	43.5	16.1	47.5	47.3	57.5	11.1	56.9	53.0	64.5
Jilin	27.5	56.6	37.3	40.8	36.0	9.8	11.7	14.3	26.0	16.9	17.4	21.2	16.0	25.8	23.1	28.1	11.0	31.4	25.9	31.6
Chongqing	28.8	54.7	32.3	36.0	35.5	8.9	11.4	13.9	25.5	15.3	17.4	21.2	15.5	23.2	23.4	28.5	10.5	27.9	26.4	32.1
Shanghai	23.0	54.3	15.0	16.7	35.4	4.2	9.0	10.9	25.4	7.2	13.7	16.7	15.4	10.9	18.5	22.5	10.4	13.1	20.9	25.4
Shananxi	37.3	54.2	43.9	48.5	35.4	11.4	14.5	17.6	25.4	20.2	22.2	27.1	15.4	31.3	30.0	36.5	10.4	38.1	33.8	41.2
Liaoning	44.7	53.5	58.6	64.8	35.2	15.0	16.8	20.5	25.2	26.8	26.1	31.8	15.2	41.7	35.3	43.0	10.2	50.9	40.0	48.6
Hunan	65.7	53.2	69.2	76.8	35.2	18.0	24.5	29.9	25.2	31.8	38.1	46.4	15.2	49.2	51.7	63.0	10.2	59.9	58.5	71.2
Sichuan	80.4	51.6	86.5	98.8	34.8	20.7	27.9	34.0	24.8	39.8	44.6	54.3	14.8	63.5	61.2	74.5	9.8	75.9	69.5	84.6
Zhejiang	57.4	49.5	39.2	44.5	34.3	9.7	18.0	21.9	24.3	18.5	29.9	36.4	14.3	29.3	41.8	50.8	9.3	35.6	47.7	58.1
Qinghai	5.2	49.3	6.8	7.6	34.3	1.6	1.6	2.0	24.3	3.1	2.7	3.3	14.3	4.9	3.8	4.6	9.3	6.1	4.3	5.3
Heilongjiang	38.3	47.2	49.6	57.1	33.8	9.3	10.6	12.9	23.8	21.0	18.5	22.6	13.8	36.0	26.5	32.2	8.8	44.5	30.4	37.1
Ningxia	6.3	46.1	6.6	7.5	33.6	1.4	1.6	2.0	23.6	2.9	2.9	3.6	13.6	4.8	4.3	5.2	8.6	6.0	4.9	6.0
Jiangxi	44.6	42.7	41.3	48.1	32.7	7.8	9.2	11.2	22.7	18.1	18.4	22.4	12.7	31.1	27.6	33.6	7.7	39.0	32.2	39.2
Gansu	25.6	42.6	24.8	29.1	32.7	4.6	5.2	6.4	22.7	10.8	10.5	12.8	12.7	18.6	15.8	19.3	7.7	23.3	18.5	22.5
Inner Mongolia	24.7	42.4	31.4	36.8	32.7	5.3	5.0	6.1	22.7	13.4	10.1	12.3	12.7	23.7	15.2	18.5	7.7	29.3	17.8	21.6
Guangxi	48.2	41.8	52.7	61.7	32.6	9.7	9.3	11.3	22.6	23.0	19.3	23.4	12.6	39.9	29.2	35.6	7.6	50.2	34.2	41.7
Guangdong	114.7	33.7	90.6	112.7	30.7	6.5	7.2	8.7	20.7	35.2	30.9	37.6	10.7	71.9	54.7	66.5	5.7	89.9	66.5	81.0
Guizhou	29.3	32.7	32.0	41.2	30.4	1.2	1.4	1.7	20.4	12.7	7.4	9.1	10.4	26.7	13.5	16.5	5.4	31.5	16.6	20.2
Yunnan	45.6	30.1	35.7	47.0	29.8	–	0.3	0.4	19.8	12.6	9.7	11.8	9.8	29.3	19.2	23.3	4.8	35.4	23.9	29.1
Fujian	36.9	28.5	26.5	35.4	29.5	–	–	–	19.5	9.4	6.9	8.4	9.5	22.5	14.6	17.7	4.5	26.5	18.4	22.4
Tibet	3.0	27.8	2.4	3.5	29.3	–	–	–	19.3	0.7	0.5	0.6	9.3	2.1	1.2	1.4	4.3	2.4	1.5	1.8
Hainan	2.7	20.4	1.3	2.1	27.6	–	–	–	17.6	0.2	0.2	0.2	7.6	1.2	0.7	0.9	2.6	1.3	1.0	1.2
China	1352	53	1515	1699	35	364	549	668	25	679	828	1008	15	1073	1108	1349	10	1291	1248	1519

WHO-IT1, IT2, IT3 and AQG are visualized in Fig. 6. The Northern China exhibited higher mortality rates (10^{-5} y^{-1}) benefits than the Southern China, especially in Hebei, Henan, the Northeast China, and Xinjiang provinces. Considering the population distribution, greater mortality number benefits in Henan, Shandong, Hebei, Jiangsu, Hubei and Sichuan provinces were observed (Table 1) if China meets the first stage of WHO interim targets (IT1) or the CAAQS II standard. Additionally, greater mortality benefits in Shandong, Henan, Guangdong, Hebei, Sichuan and Jiangsu provinces were observed (Table 1) if China meets the WHO AQG standard.

If the PWA $PM_{2.5}$ concentrations in China meets the WHO IT-1 (or Chinese Ambient Air Quality Standard), IT-2, IT-3, and AQG standards, it would be possible to achieve mortality benefits of 24.0%, 44.8%, 70.8%, 85.2% reduction of the total mortalities (1.52 million) and premature deaths attributable to $PM_{2.5}$, respectively. Additionally, morbidity benefits from meeting WHO $PM_{2.5}$ Standards are presented in Table 1.

4. Discussion

Air pollution in China has always been a hotspot issue because of its high pollutant anthropogenic emissions and the largest population in the world. The improvement of air quality in China has substantial global health benefits from the perspective of the global burden of disease (Apte et al., 2015). Following the comparative risk assessment framework of the GBD study (Murray et al., 2012), we estimated the health burden attributable to $PM_{2.5}$ across China during 2014–2016 and health benefits from meeting WHO $PM_{2.5}$ Standards by a comprehensive integration of ground measurements, census data, baseline mortality rates and population regression statistics. We found that the annual average mass concentration of ground $PM_{2.5}$ showed significant geographic variation across China, suggesting a huge spatial heterogeneity of $PM_{2.5}$ pollution in China, which was in agreement with both previous both monitoring-based and satellite-based studies (Ma et al., 2015; Zhao et al., 2016; Zhou et al., 2016b). $PM_{2.5}$ in 2015 contributed as much as 30.2% of total deaths combining IHD, stroke, COPD, and LC. In GBD 2015 study (Wang et al., 2016b), the total deaths caused by IHD, stroke, COPD, and LC accounted for 51.4% of the all cause deaths. Thus, ambient $PM_{2.5}$ exposure in 2015 was associated with 15.5% of all cause deaths which is almost one half of estimates (32%) in 74 leading cities study in 2013 (Fang et al., 2016). The Attributable fractions exhibited wide ranges across China and were comparable with those of the GBD studies (Burnett et al., 2014), with the PWA values of 40.3%, 33.1%, 26.8, 23.9%, and 18.7% for total stroke, ALRI (<5yr), IHD, LC, and COPD deaths, respectively.

According to the cause-specific mortality in the 2013 GBD project (Collaborators, 2015; Zhou et al., 2016a), the leading causes of years of life lost (YLLs) in China were stroke, followed by IHD, COPD and LC (Milner and Wilkinson, 2016). In addition, the percentages of stroke, IHD and LC of all death causes increased from 1990 to 2013 (Fig. S4). Historical concentrations of PM in 31 Chinese capital cities from 2001 to 2010 (Kan et al., 2012; Zhou et al., 2016b) showed a trend of a 23% reduction (70–55.8 μg m^{-3}) within this 7-year period, suggesting ambient $PM_{2.5}$ pollution was more serious over the last decade. However, recent studies of satellite-based $PM_{2.5}$ in China showed an increasing trend of $PM_{2.5}$ concentration from 2004 to 2013 (Ma et al., 2015) and 1990–2013 (Brauer et al., 2016), which was exactly the opposite of the ground monitoring data. This critical dispute remains to be verified by more studies on the variation trends of historical $PM_{2.5}$ concentrations. However, the average concentrations of $PM_{2.5}$ over the last decade were still far beyond 55 μg m^{-3}, which was much higher than the PWA $PM_{2.5}$ concentration (53 μg m^{-3}) in year 2015. In this study, the PWA attributable mortality rates (AMR, 10^{-5} y^{-1}) were 112.0 in current year analysis, and 124.3 in 10-year time lag analysis. The Mortality attributable to $PM_{2.5}$ in 10-year time lag analysis (1.7 million) was 12% higher than the current year analysis (1.5 million). This result suggested that the health burden associated with ambient $PM_{2.5}$

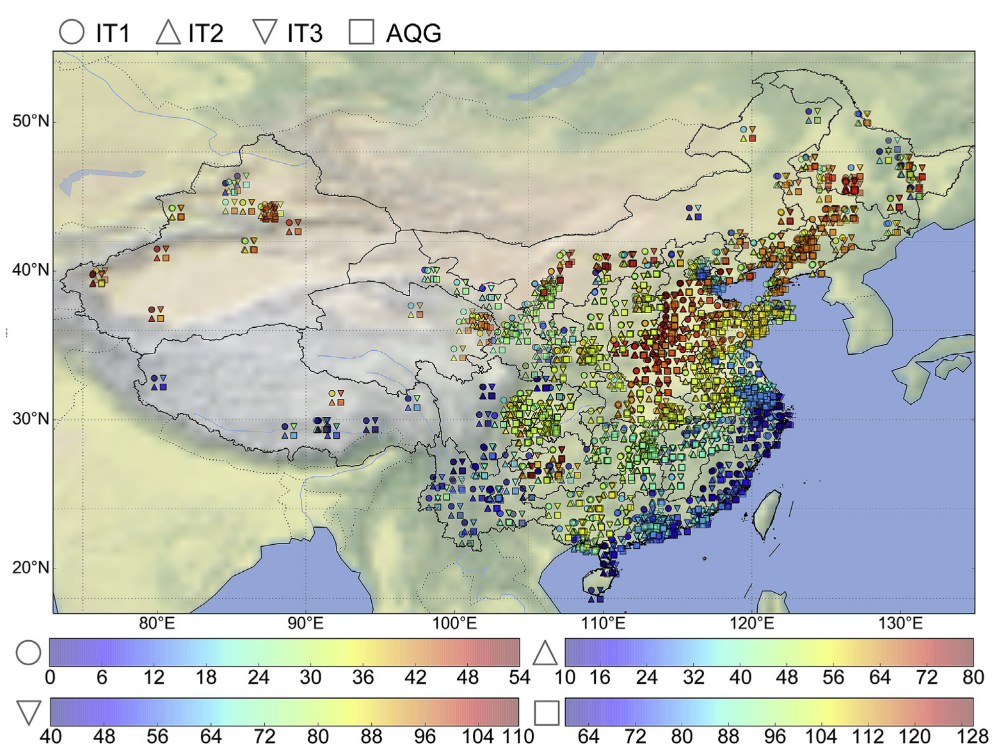

Fig. 6. Mortality rate (10^{-5} y^{-1}) benefits of meeting WHO interim targets (IT1, IT2, IT3 and AQG).

exposure in lagged analysis over the last decade were much greater than our main analysis in 2015.

Although China has been coming into a new stage, from controlling total environmental capacity to controlling both total environmental capacity and environmental quality, a great health burden caused by $PM_{2.5}$ will still play an increasingly significant role in Chinese social and economic development, considering the 5–15 lagged years (Lepeule et al., 2012; Tie et al., 2009) between long-term exposure to $PM_{2.5}$ and mortality caused by stroke, LC and COPD.

Previous China's subnational study for the GBD 2013 (Zhou et al., 2016a) suggested that China could be divided into five regions (so-called nations) on the basis of mortality rates and life expectancy (Milner and Wilkinson, 2016). This study also presented the great health inequalities caused by exposure to $PM_{2.5}$ due to the spatial variety in both the mortality baselines and $PM_{2.5}$ pollution across China. The hot spots of the attributable mortality rate (10^{-5} y^{-1}) could be clearly observed in Hebei, Henan and Shandong provinces (Fig. 5). Those areas also had a relatively high density of population. The spatial variation in environmental health risks caused by $PM_{2.5}$ should be considered by the Chinese government when attempting to set emission reduction targets and addressing the problem of inequality in health service.

Our study revealed that $PM_{2.5}$ pollution in China contributed to 1.5 (1.7 in 10 year-lag analysis) million total deaths, which is higher than the GBD 2015 estimates (1.1 million), accounted for almost one third of the global deaths (4.2 million) attributable to particulate matter pollution in 2015 (Forouzanfar et al., 2016). Our estimates were comparable with previous studies which showed that premature deaths attributed to $PM_{2.5}$ across China were 1.2 million in 2012 (Liu et al., 2017), 1.37 million in 2013 (Liu et al., 2016), 1.6 million in 2014 (Rohde and Muller, 2015).

Even the PWA $PM_{2.5}$ concentration would achieve the Chinese National Grade II standard (35 μg m^{-3}) in the next few years, $PM_{2.5}$ would still contribute to 1.2 million total deaths, and it would continue to predominate in the global burden of disease attributable to $PM_{2.5}$. If the population-weighted $PM_{2.5}$ concentrations in China were to meet the WHO IT-1 (or Chinese Ambient Air Quality Standard), IT-2, IT-3, and AQG, it would be possible to achieve mortality benefits of 24.0%, 44.8%, 70.8%, 85.2% of the total mortalities and premature deaths attributable to $PM_{2.5}$, respectively. Thus, China should not loosen its $PM_{2.5}$ standard (35 μg m^{-3}) (Zhou et al., 2010), and continue to control total emissions to improve air quality to meet the first stage (IT1) of WHO interim targets considering its huge health and climate benefits.

However, there were some limitations and uncertainties in our study. Firstly, since the annual averaged mass concentrations of ground $PM_{2.5}$ across China showed a wide range, the IER model was used instead of the Chinese specific linear model (Cao et al., 2011). Cohort studies based China-specific nonlinear concentration-response model should be developed in the future, even though the IER model yielded reasonable predictions in China and other highly polluted areas (Burnett et al., 2014; Liu et al., 2017).

Secondly, chemical compositions in $PM_{2.5}$ were neglected in the IER model. However, the toxicity of $PM_{2.5}$ varied with geography, according to its chemical composition. From the published studies of chemical compositions (shown in Fig. 7), the average percentages of organic matter (OM), sulfate, nitrate, ammonium, elemental carbon (EC), crustal and unidentified species in China (Fig. S6) were 22.6 ± 5.9%, 17.8 ± 5.5%, 10.1 ± 4.1%, 7.3 ± 2.1%, 6.1 ± 2.8%, 18.1 ± 10.0% and 18.0 ± 6.7, respectively. Secondary aerosol (SNA: sulfate, nitrate and ammonium) was the most abundant species, accounting of 37.0± 7.0% in BTH, 36.3 ± 10.3% in YRD, 41.4± 1.4% in PRD and 36.6 ± 9.0% of the total $PM_{2.5}$ mass in China, which was consistent with previous studies (Cheng et al., 2016b; Zhou et al., 2016b) and slightly higher than the 30% in the global population-weighted composition (Philip et al., 2014). However, long-term exposure to $PM_{2.5}$ chemical components are less well understood and need to study further (Lepeule et al., 2012; Philip et al., 2014). Incomplete combustion of biomass fuel is responsible for the high prevalence of COPD in Chinese never-smokers (Guan et al., 2016; Tao et al., 2012), and unvented indoor coal burning is strongly associated with increased risk of LC and COPD (Guan et al., 2016; Shen et al., 2009). Fossil fuel combustion-associated $PM_{2.5}$ pollution were reported to have an appreciable influence on the health effects attributable to China (Cao et al., 2012), and emissions from residential energy use such as heating and cooking were the largest contribution to premature mortalities in China (32%) and the world (31%) (Lelieveld et al., 2015). Thus, the full implementation of the 'coal to natural gas' project in the entire BTH cluster might mitigate the disease burden of COPD and LC attributable to air pollution, and reducing smoking and solid-fuel use can substantially lower mortality burden of COPD and LC in China (Lin et al., 2008). More studies are needed to focus on health effects associated with long-term exposure to $PM_{2.5}$ chemical components and source contributions (Fig. S7), and assessment of health benefits of government's strategies like the 'coal to natural gas' project.

Thirdly, highly density state-controlled ground monitoring stations were focused on urban areas, and only a few were focused on in suburban and rural areas (Wang et al., 2014b). The population weighted annual average concentration of ground monitoring $PM_{2.5}$ might be overestimated, since PM levels were higher at urban sites than rural ones. NAQMS should cover more rural sites in the future. Moreover, the Chinese Center for Disease Control and Prevention needs to build up bonds of cooperation with the Ministry of Environmental Protection to address health inequalities and improve health surveillance systems, by integrating environmental exposure factors and geographic information, since our health is a function of where we live (Goenka and Andersen, 2016).

According to observed $PM_{2.5}$ data from NAQMS during this three-year study period, the $PM_{2.5}$ pollution have improved significantly. However, persistent hazy events frequently occurred during cold winter periods especially in the North China Plain. Photochemical oxidation of VOCs and NO_x from urban emissions and SO_2 from regional industrial sources were primary responsible for the large secondary formation during the severe $PM_{2.5}$ events in China (Cheng et al., 2016a; Guo et al., 2014; Huang et al., 2014a). Haze and premature mitigation could be achieved by intervening in the sulfate information process with NH_3 and NO_2 emission control measures (Wang et al., 2016a). In addition, health benefits of active commuting (cycling, walking) from physical activity are larger than risk from an increased inhaled dose of $PM_{2.5}$ (Cepeda et al., 2016; de Nazelle et al., 2011). The good phenomenon is that bicycle-sharing system are being undertaken in many Chinese cities, such as Wuhan, Hangzhou, Beijing, Shanghai, Guangzhou and Shenzhen. With accelerating urbanization, active transportation and mass transit system are the solutions for cleaner air and reducing health burden associated with ambient air pollution (Kelly and Zhu, 2016; Normile, 2016).

5. Conclusions

With direct measurements of $PM_{2.5}$ from more than one thousand NAQMS during entire three years (2014.01.01–2016.12.31), the health burden attributable to ambient $PM_{2.5}$ and health benefits from achieving WHO interim targets (IT1, IT2, IT3, AQG) were estimated across China. $PM_{2.5}$ in 2015 contributed as much as 30.2% to total deaths combining IHD, stroke, COPD, and LC, 15.5% to all cause deaths. The Attributable fractions exhibited wide ranges across China and were comparable with those of the GBD studies,

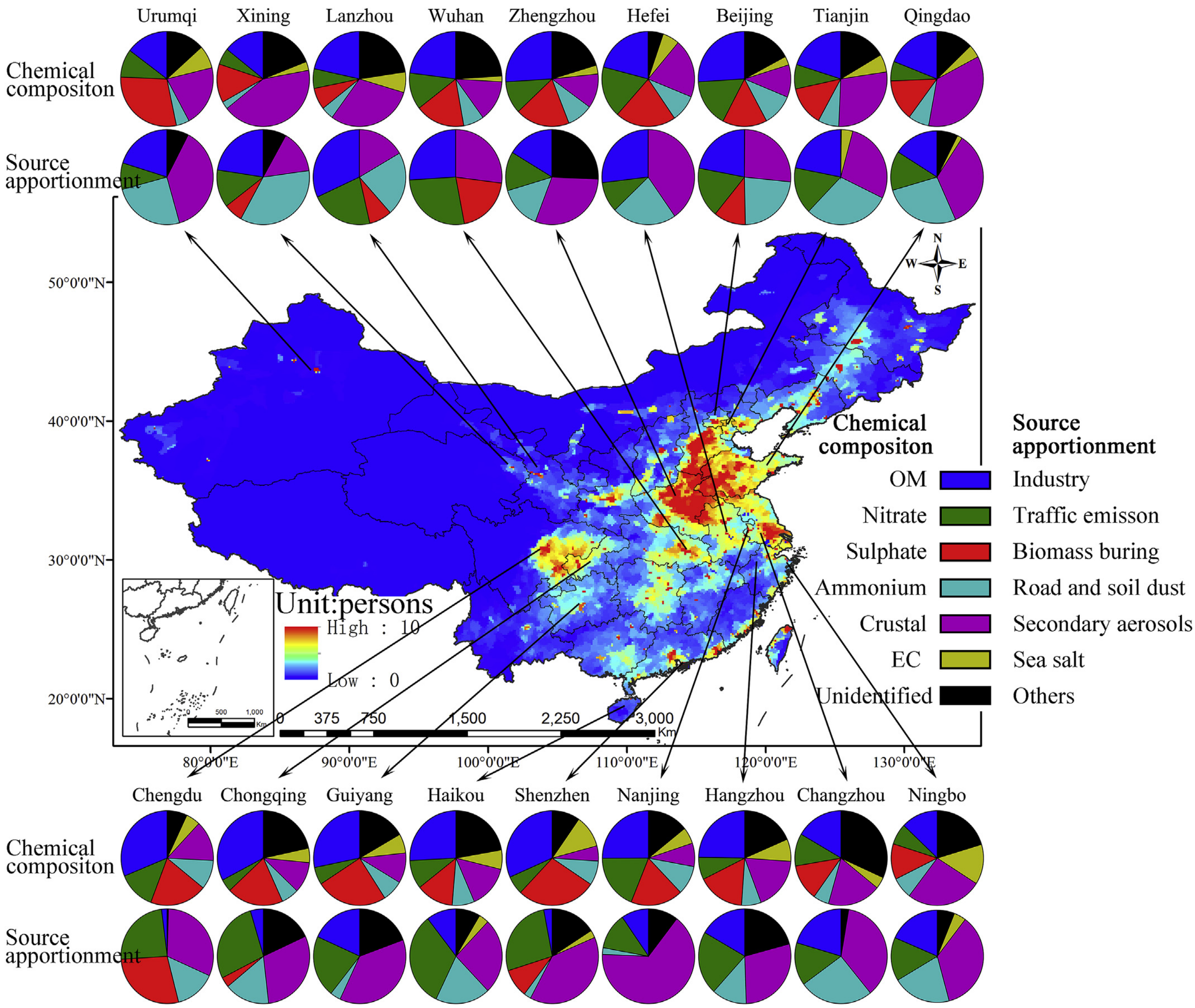

Fig. 7. Spatial distribution (0.1° × 0.1°) of total mortalities attributable to $PM_{2.5}$ in 2015, chemical composition and source apportionment of $PM_{2.5}$. OM (organic matter) = 1.4 × OC, EC: elemental carbon, Crustal = 2.2Al + 2.49Si + 1.63Ca + 2.42Fe + 1.94Ti, Unidentified = $PM_{2.5}$ mass - OM - EC - Nitrate - Sulphate - Ammonium - Crustal. The sampling date and references for each city are as follows: **Beijing**, 2010.01–2010.12, (Yu, 2013); **Changzhou**, 2013.04–2014.04, (Wang, 2015b); **Chengdu**, 2009.04–2010.01, (Zhang et al., 2013); **Chongqing**, 2012.02–2012.12, (Ren et al., 2014); **Guiyang**, 2013.10–2014.06, (Wang, 2015c); **Haikou**, 2011.12–2012.04, (Song et al., 2015); **Hangzhou**, 2006.01–2006.12, (Bao and Feng, 2010); **Lanzhou**, 2014.01–2014.12, (Wang et al., 2016c); **Nanjing**, 2011.08–2012.03, (Chen et al., 2015); **Ningbo**, 2010.01–2010.10, (Xiao et al., 2012); **Qingdao**, 2011.10–2012.08, (Wu et al., 2013); **Shenzhen**, 2009.01–2009.12, (Huang et al., 2014b); **Tianjin**, 2014.05–2015.01, (Tang, 2014); **Urumqi**, 2013.01, (Wang et al., 2014a); **Xining**, 2014.02–2014.09, (Dou et al., 2016); **Zhengzhou**, 2013.13–2014.10, (Wang, 2015a).

with the population-weighted average (PWA) values of 40.3%, 33.1%, 26.8, 23.9%, and 18.7% for total stroke, ALRI (<5yr), IHD, LC, and COPD deaths, respectively. The PWA attributable mortality rates (AMR, 10^{-5} y^{-1}) were 112.0 in current year analysis, and 124.3 in 10-year time lag analysis. The Mortality attributable to $PM_{2.5}$ in 10-year time lag analysis (1.7 million) was 12% higher than the current year analysis (1.5 million).

Our study also estimated site-specific annual $PM_{2.5}$ concentrations in scenarios of achieving WHO ITs and AQG. Greater mortality benefits in Henan, Shandong, Hebei, Jiangsu, Hubei and Sichuan provinces were observed if China meets the first stage of WHO interim targets (IT1) or CAAQS II standard. Additionally, greater mortality benefits in Shandong, Henan, Guangdong, Hebei, Sichuan and Jiangsu provinces were observed if China meets WHO AQG standard.

The mortality benefits will be 24.0%, 44.8%, 70.8%, and 85.2% of the total current mortalities (1.5 million) when the PWA $PM_{2.5}$ concentrations in China meets the WHO IT-1, IT-2, IT-3, and AQG, respectively. We expect air quality modeling and cost-benefits analysis of emission reduction scenarios and corresponding health benefits in meeting the site-specific annual $PM_{2.5}$ concentrations (WHO IT-1, IT-2, IT-3, and AQG) this study raised. This could help Chinese governments to make better decisions and policies to build environment towards health, equity and habitat (Jiang et al., 2015).

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The author declare they have no completing financial interests.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.01.060.

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