Environment International 161 (2022) 107110

Contents lists available at ScienceDirect

Environment International

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

Full length article

What drives long-term $PM_{2.5}$-attributable premature mortality change? A case study in central China using high-resolution satellite data from 2003 to 2018

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ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
$PM_{2.5}$
Satellite remote sensing
Health burden
Spatiotemporal variation
Decomposition analysis

ABSTRACT

Ambient $PM_{2.5}$ was reported to be related to numerous negative health outcomes, leading to adverse public health impacts in many countries such as China. Despite the apparent reduction in $PM_{2.5}$ levels over China due to its emission control policies in recent years, the health burdens were not reduced as much as expected. This calls for a comprehensive analysis to explain the reasons behind to provide a useful reference for formulating effective emission control strategies. Taking central China as an example due to its large population and high levels of $PM_{2.5}$, this study quantified the spatiotemporal dynamics of premature mortality associated with $PM_{2.5}$ pollution in central China for each year during 2003–2018 and applied a decomposition analysis to dissect the contribution of various driving factors including ambient $PM_{2.5}$ level, demographic distribution and baseline incidence rate of four diseases related to air pollution. Results show significant spatiotemporal variations in $PM_{2.5}$-attributed health impact in central China, including Henan, Hubei, and Hunan provinces. Five Henan cities had the largest $PM_{2.5}$-attributable premature mortality (~8–12 K premature mortalities), while three Hubei cities and one Hebei city had the least chronic $PM_{2.5}$-related all-cause mortality numbers (<1 K mortalities). Throughout the study period, the $PM_{2.5}$-caused premature mortality decreased by 54 K, in which changes in $PM_{2.5}$ levels and baseline incidence rates of stroke and chronic obstructive pulmonary disease contributed to the positive effect, whereas demographic changes and baseline incidence rate change of ischemic heart disease and lung cancer brought a countervailing effect. Our findings suggest more dynamic and comprehensive policies and measures that take into account spatiotemporal variations of health burden for effective alleviation of the health impact of $PM_{2.5}$ pollution in the country.

1. Introduction

Long-term exposure to ambient fine particulate matter (or $PM_{2.5}$, referring to particles with an aerodynamic diameter of < 2.5 μm suspended in the air) has been associated with premature mortality resulted from respiratory and cardiovascular disease outcomes (Brook et al. 2010; Pope 3rd 2000; Yim et al. 2022). Global Burden of Disease (GBD) reported that $PM_{2.5}$ was one of the top eight lethal risks in 2017, causing 2.94 million premature mortalities worldwide (GBD Collaborators 2018). Thus, exposure to clean air is critical for the human body, and measures and policies are in need to secure sustainable development and benefit public health.

With the rapid urbanization and industrialization in the past couple of decades (Wang et al. 2019; Yim et al. 2019a; Yim et al. 2019c), $PM_{2.5}$ pollution has become one of the leading environmental problems in China (Liu et al. 2018; Shi et al. 2020; Yang et al. 2019; Yim et al. 2019b). According to (Hoesly et al. 2018), China is one of the most air-polluted countries (Li et al. 2020; Luo et al. 2018; Ning et al. 2020; Tong

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https://doi.org/10.1016/j.envint.2022.107110
Received 29 September 2021; Received in revised form 2 January 2022; Accepted 21 January 2022
Available online 5 February 2022

et al. 2018; Wang et al. 2020; Yim et al. 2010) and emits 18–35% of global pollutants into the atmosphere. To remedy this issue, the Chinese government implemented a series of air pollution control policies (Ma et al. 2019). However, the control policies implemented before 2013 were relatively loose, primarily focusing on emission control of e.g., SO_2 and industrial dust. From 2013 onwards, China started stringent measures and regulations to fight against air pollution. $PM_{2.5}$ was the first time regarded as one criteria pollutant, adding the national ambient air quality standards (NAAQS) where the annual maximum $PM_{2.5}$ concentration is 35 μg /m^3 (Lin et al. 2018; Ma et al. 2019). The Air Pollution Prevention and Control Action Plan (APPCAP) was enacted between 2013 and 2017, targeting to decrease $PM_{2.5}$ concentration in cities by at least 10% in those years (http://www.gov.cn/zwgk/2013–09/12/content_2486773.htm). A three-year plan entitled "battle of protecting blue sky" was subsequently implemented during 2018 to 2020 to further lower the $PM_{2.5}$ concentration by 18% for the prefecture-level cities that yet satisfied the NAAQS compared with 2015 (http://www.gov.cn/zhengce/content/2018–07/03/content_5303158.htm). According to the previous studies (He et al. 2021; Ma et al. 2019), China has touched the target of air pollution control and the decreasing trend in $PM_{2.5}$ is observed, especially from 2013. However, the health benefits of the $PM_{2.5}$ improvement due to the stricter air pollution policies (refer to the plans and measures implemented after 2013) are not clear. It is of great importance to quantitatively assess the effect of those actions on air pollution improvement for informing future air pollution policymaking.

Assessment of $PM_{2.5}$–attributable premature mortality depends on several factors, e.g., $PM_{2.5}$ level, population distribution, age structure, and baseline incidence rate (Burnett et al. 2014; GBD Collaborators 2018; Peng et al. 2016). In addition to the obvious change in ambient $PM_{2.5}$ concentration, the other impact factors have also been experiencing significant changes, e.g., population growth and aging due to improvement in healthcare, and rural–urban migration due to urbanization, etc. Previous studies tried to understand the health effect from one individual factor. For instance, the health benefits of the stricter policies were uncovered by isolating the effect of the $PM_{2.5}$ reduction on the decline in mortality by fixing other factors (Zhang et al. 2019; Zou et al. 2019). Liang et al. (2020) and Lu et al. (2019) used the trend of $PM_{2.5}$ levels to approximate the premature mortality related to long-term $PM_{2.5}$ exposure in China. However, the trend in $PM_{2.5}$-related mortality is a result of changes in contributing factors (e.g., changes in $PM_{2.5}$, population distribution, lifestyle) and the interaction among these factors, which may lead to a countervailing effect on mortality change. Most of the previous research did not separate the relative contributions of the factors to the premature mortalities and yet did not directly quantify the effects of changes in their driving factors on health burden. It is therefore necessary to conduct a comprehensive analysis to investigate the dynamics of the driving factors for $PM_{2.5}$ premature mortality and also to differentiate their relative contributions to safeguard the achievement of sustainable development.

As for the exposure levels, several methods have been applied to evaluate the levels of $PM_{2.5}$ exposures. Ground-based observation data and simulation-based outputs are the popular way to provide the input data for estimating the health impact caused by $PM_{2.5}$ (Fang et al. 2016; Gu and Yim 2016; Gu et al. 2020; Hou et al. 2019; Maji et al. 2018; Xue et al. 2019a). However, the ground monitoring data come from fixed sites, and the spatial resolutions of simulation output are usually coarse (e.g., 10 km and coarser), which cannot sufficiently capture the spatial variability in $PM_{2.5}$, especially for urban areas (Chudnovsky et al. 2013; Ma et al. 2016b). Consequently, the difference in exposure level in an urban city was overlooked, and it is insufficient to support the accurate estimation of the $PM_{2.5}$-related health burden. With the spatiotemporal continuous observations provided by satellite remote sensing, satellite-derived $PM_{2.5}$ has been an effective alternative way to offer high-spatial-resolution exposure estimates (e.g., 1 km) and to break through the temporal coverage bottleneck of $PM_{2.5}$ monitoring data (Kloog et al. 2014; Ma et al. 2016a; Van Donkelaar et al. 2016; Wei et al. 2021). In China, the measured $PM_{2.5}$ data only dated back to 2013, which plagued most $PM_{2.5}$-related health studies focusing on the years after 2013 (Maji et al. 2018; Song et al. 2017; Xue et al. 2019a; Zou et al. 2019). Therefore, improved $PM_{2.5}$ estimates with a finer spatial resolution and covering couples of decades are indispensable to lower the bias of estimates of health burden by $PM_{2.5}$, allowing long-term health effect studies.

Even though the central China region, including Henan, Hubei, and Hunan provinces, possesses a relatively small geographical extent, equivalently ~ 6% of the territory, the region has a large population, i.e., ~16% of the total Chinese population. Together with high levels of $PM_{2.5}$ exposure, all three provinces have been experiencing very high numbers of $PM_{2.5}$-attributable premature mortality. Typically, most previous studies have identified that Henan province had the largest health burden related to $PM_{2.5}$ exposure in China, with approximately 100 thousand premature mortalities per year (Zou et al. 2019). In the light of this, comprehensively understanding the changes of premature mortality associated with $PM_{2.5}$ in central China and the relative contribution of the impact factors are critical to enlighten the health effects related to changes in $PM_{2.5}$, population, and medical conditions and guide future actions on improving $PM_{2.5}$-related health burden for this region and for the whole country.

Focusing on the implementation of stricter air pollution control policies, it is intriguing to understand (1) how the $PM_{2.5}$-attributable premature mortality and its driving factors spatiotemporally changed in central China during the long-term period of 2003–2018, especially in the period after 2013 when tightening air quality policies have been put into place; (2) how much health benefit/burden was caused by changes in the driving factors and to what degree the $PM_{2.5}$ reduction in recent six years alleviated the health burden in central China; and (3) what measures and actions will be in need in the future to further improve $PM_{2.5}$-attributable health burden in central China. This study combined 1-km high-spatial-resolution $PM_{2.5}$ estimates, Landscan 1-km population distribution, and baseline incidence rate from the world health organization to address the aforementioned questions.

2. Methods

2.1. Study area

Central China, located in the middle and lower reaches of the Yellow River and the middle reaches of the Yangtze River, includes three provinces: Henan, Hubei, and Hunan. As one of the densely populated regions in the world, it covers ~ 6% of land and accounts for ~ 16% of the total population in China. Topographically, most areas in this region lie on flat terrain with an altitude below 200 m, but it is surrounded by highlands to the west with an average elevation of 500–1000 m. The location of the central China region with terrain and population distributions is illustrated in Fig. S1.

2.2. High-resolution $PM_{2.5}$ estimation

Taking advantage of the MODIS high-resolution AOD product retrieved by the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm, the surface 1-km $PM_{2.5}$ data were estimated by a space–time regression model. Due to the fine spatial scale of 1 km, the MAIAC AOD data allow the local-scale aerosol gradient that other coarse-resolution aerosol products lose, making it possible to characterize the details of regional and even local particulate pollutions (Chudnovsky et al. 2013). Liu et al. (2019) have evaluated the accuracy of MAIAC AOD data and found a good agreement (correlation coefficient $r > 0.9$) between the satellite aerosol retrievals over China from 2000 to 2017 and ground measurements. Thus, we used this dataset to generate the daily surface $PM_{2.5}$ concentration for our analyses.

Statistical methods, with a general high estimation accuracy, are

widely applicable to surface $PM_{2.5}$ reconstruction. However, since surface air quality measurement before 2013 is not publicly available in China, it is difficult to employ a statistical approach to infer ambient concentration preceding 2013 in the country due to the lack of measured constraints for model development. To address this issue, we calibrated and validated a spatiotemporal model (geographically and temporally weighted regression model, GTWR) that was improved by capitalizing on the periodic characteristic within the data to generate the historical daily $PM_{2.5}$ concentration from 2003 to 2018. The MAIAC AOD, meteorological parameters [including relative humidity (RH), surface temperature (ST), surface wind speed (SWP), and planetary boundary layer height (PBLH)] and land use-related parameters [including normalized difference vegetation index (NDVI) and elevation] were input as independent variables for the spatiotemporal modeling (the data source for the explanatory variables are provided in Table S1). In addition to the first-order variables that have been popular in previous models (e.g., AOD, RH, ST, SP), non-linear interaction between AOD and meteorological parameters such as AOD × ST was introduced into the space–time regression model to tackle the complicated association between ground $PM_{2.5}$ and satellite AOD. Here we briefly describe the model development and validation process because it has been documented in detail in our previous study (He et al. 2020).

An annual-based cross-validation (CV) method was applied to evaluate the model errors quantitatively, and our long-term estimates were found to agree well with in-situ measurements with R^2 of 0.59 at a daily scale and 0.73 at a monthly scale (Fig. S2). The annual-based CV is the state-of-the-art validation approach to evaluating model performance outside the model fitting years. Our retrieved data achieved promising accuracy comparable to prior coarse-resolution concentration at a grid of 0.1° × 0.1° across China ($R^2 = 0.41 \sim 0.71$) (Ma et al. 2016a; Xue et al. 2019b) and 1-km results over Beijing and Yangtze River Delta ($R^2 = 0.42 \sim 0.72$) (Liang et al. 2018; Xiao et al. 2017). The spatial distribution maps of 16-year $PM_{2.5}$ estimates in the study region during the 2003–2018 period are presented in Fig. S3, showing the $PM_{2.5}$ local contrasts in the study region. As a result, our satellite-retrieved high-resolution $PM_{2.5}$ data are reliable for further analyses, offering a good opportunity to analyze air pollution in urban areas with a complex topography and to assess the health burden caused by ambient fine particulate matter.

2.3. Health impact assessment method

Our health impact assessment included four diseases, i.e., stroke, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), and lung cancer (LC). To link the concentration of fine particulate matter to the adverse health outcomes, we calculated the number of premature mortality attributable to the chronic exposure to $PM_{2.5}$ with the use of an epidemiological exposure–response function shown as follows:

$$Mort_{i,t} = IR_{p,t} \times AF_{i,t} \times POP_{i,t} \quad (1)$$

where $Mort_{i,t}$ represents the premature mortalities caused by a disease (i.e., stroke, IHD, LC, and COPD) due to the long-term $PM_{2.5}$ exposure in the grid cell i for the year t; $IR_{p,t}$ is a disease-specific baseline incidence rate for the province p in the year t, which was obtained from the data provided by GBD Study (Zhou et al. 2016); $POP_{i,t}$ is the annual population over 25 years old exposed to $PM_{2.5}$ over each grid cell; $AF_{i,t}$ is the attributable fraction over grid cell i in the year t, which can be computed as Eq. (2):

$$AF_{i,t} = (RR_{i,t} - 1)/RR_{i,t} \quad (2)$$

where $RR_{i,t}$ represents the relative risk of $PM_{2.5}$-attributed premature mortality for a specific disease. In this study, $RR_{i,t}$ was estimated by the integrated exposure–response model derived from Burnett et al. (2014), which is expressed as follows:

$$RR_{i,t} = 1 + \alpha \bullet \left\{ 1 - \exp\left[-\beta \left(X_{i,t} - X_0 \right)^{\delta} \right] \right\} \quad (3)$$

where $X_{i,t}$ and X_0 are respectively the pollutant concentration (μg/m^3) over the grid cell i in the year t and the threshold concentration, below which no additional risk was assumed to exist.

Our study adopted the annual population distribution data with a 1-km resolution for the 2003–2018 period from the LandScan High Resolution Global Population Data Set (https://landscan.ornl.gov/). The gridded population data were successfully used in previous works to study the exposure and health impact due to air pollution (Lin et al. 2016; Lu et al. 2017). The total population within each province from the annual Landscan gridded data was corrected by the values provided by the Chinese Statistical Yearbook of 2003–2018 (http://www.stats.gov.cn/tjsj/ndsj/). The parameters α, β, and δ in Eq. (3) were fitted from the cohort study and summarized in Burnett et al. (2014) and Song et al. (2017). The annual ratios of 25 years old over the entire population between 2003 and 2018 were derived from the national age structure data reported by the official yearbooks.

2.4. Decomposing the contributions of driving factors

We separated the effects of $PM_{2.5}$ concentration, population, and baseline incidence rate of individual diseases on the $PM_{2.5}$-attributable premature mortality change using the decomposition approach adopted by GBD (Cohen et al. 2017; GBD Collaborators 2018). The contribution of each factor was estimated by sequentially changing factors from base year to target year in the mortality equation. Since the sequence of changing factors may affect the estimated contribution, we performed the decomposing process under all six possible sequences of the three factors, and the final estimated contribution from the three factors was the average value of the results from the six possible sequences. The decomposing processing is briefly summarized in Fig. S4. It is worth noting that the impact factors may interact and influence each other. For example, air pollutant emissions are strongly associated with population, and thus population would have a remarkable impact on the levels of $PM_{2.5}$; exposure to $PM_{2.5}$ itself would impact the baseline incidence rate. By providing the average value of relative contribution from each impact factor, the decomposition method used in this study has removed those interacted contributions, and each impact factor is thus independent to one another (GBD Collaborators 2018).

3. Results

3.1. Changes in underlying factors

Fig. 1 presents the spatiotemporal changes of satellite-derived $PM_{2.5}$ concentration in central China in different periods: 2003–2012, 2013–2018, and 2003–2018. Northern Henan and eastern Hubei and Hunan provinces had most of the area having a 16-year mean concentration exceeding 55 μg/m^3. Those areas were more severely influenced by $PM_{2.5}$ pollution than the remaining areas (Fig. 1 (a-c) and S3). The annual averages in 2018 were much lower than those in 2003 in most of the study region (Fig. 1 (a) and (c)). The significant decrease was also identified by the yearly trends, with the linear slopes of concentration reduction ranging between 0.05 μg/m^3/year and 5 μg/m^3/year (p value < 0.05) in Fig. 1 (f). Note that such apparent decreasing trends primarily occurred in Hunan and eastern Hubei (p value < 0.05), and almost no statistically significant slope was found in central Hubei and most Henan due to fluctuations of $PM_{2.5}$ concentration in the past 16 study years (Fig. S5 and Fig. S6). Fig. 1 (d) and (e) demonstrate an obvious contrast in $PM_{2.5}$ changes between the 2003–2012 and 2013–2018 periods. Before implementing stricter emission control policies, upward trends were widespread in the 2003–2012 period while the slopes shifted to significantly negative in the later period in most study areas. The year-to-year variations of $PM_{2.5}$ averages at provincial (Fig. S5) and city

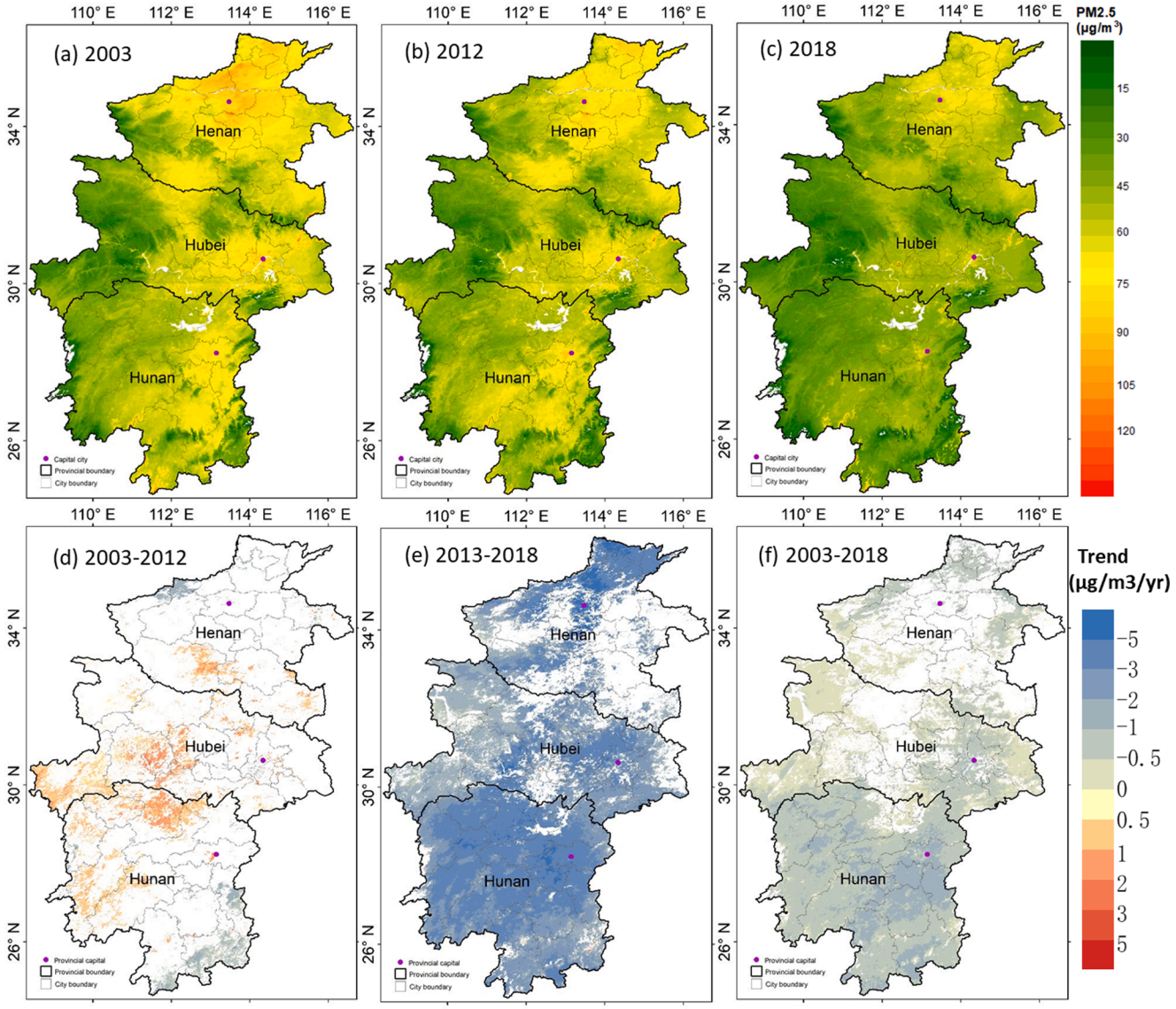

Fig. 1. Spatial distributions of (a-c) annual $PM_{2.5}$ averages in 2003, 2012 and 2018 and linear trends in monthly $PM_{2.5}$ anomaly during (d) 2003–2012, (e) 2013–2018, and (f) 2003–2018. Please note that only trends with statistical significance of p-value < 0.05 are shown in (d), (e), and (f).

(Fig. S6) levels in central China from 2003 to 2018 also demonstrate the inter-annual $PM_{2.5}$ changes in central China generally corresponded to emission and energy control policies that have been put into place, especially for the obvious reduction after 2013 due to the stricter clean air actions, e.g., the APPCAP enacted since 2013 and onwards (Lin et al. 2018). However, despite the remarkable decreases in overall particulate concentration, the $PM_{2.5}$ levels over the three provinces in 2018 still exceeded the annual NAAQS Level 2 standard of 35 μg/m^3. The ambient air pollution over central China region remains a vast challenge.

Fig. 2 shows the other two factors driving the $PM_{2.5}$-attributable premature mortality in central China from 2003 to 2018. The population over 25 years old in the three provinces possessed a stable, increasing trend with minor fluctuations. Among the three provinces, Henan maintained the largest population in the past 16 years, ranging between 62 million and 70 million in China, almost twice as much as that in Hubei (36 million ~ 43 million). The baseline incidence rates differed with stroke, IHD, COPD, and LC (Fig. 2 (b)). In general, stroke had the highest incidence rate (130 ~ 280 mortalities per 100,000 people) in central China, while LC had the lowest value (20 ~ 43 mortalities per 100,000 people). The trends of baseline incidence rate varied over specific diseases, i.e., a dramatic declining trend of stroke and COPD, an obvious upward trend of IHD, and a slight growth trend of LC.

3.2. *Estimated mortality attributed to $PM_{2.5}$*

The annual stroke-, IHD-, COPD-, and LC-induced premature mortalities attributable to ambient $PM_{2.5}$ exposure from 2003 to 2018 in central China are shown in Fig. 3. The total premature mortality due to $PM_{2.5}$ in the whole domain slowly but clearly decreased in the 16 study years from 243 K (95% CI: 107 K, 328 K) cases in 2003 to 189 K (95% CI: 86 K, 265 K) cases in 2018 with some fluctuations (Fig. 3a). The ratio of total premature mortality caused by $PM_{2.5}$ over the total all-cause mortality throughout the study period dropped from 0.17 in 2013 to 0.12 in 2018 (Fig. 3b), with a linear slope of −0.0029 (95% CI: -0.0033, -0.0025) per year (Fig. S7). Fig. 3(c) and Fig. S8 demonstrate that the long-term total $PM_{2.5}$-attributable premature mortality in each of the studied provinces also declined throughout the 16 study years with some fluctuations, and the largest annual value was observed in the Henan province. The $PM_{2.5}$-attributable mortalities due to the four diseases had different temporal profiles. The regional $PM_{2.5}$-related stroke mortality continued to drop from 143 K in 2003 to 103 K in 2018, associated with the percentage of total $PM_{2.5}$-attributable mortality due to stroke

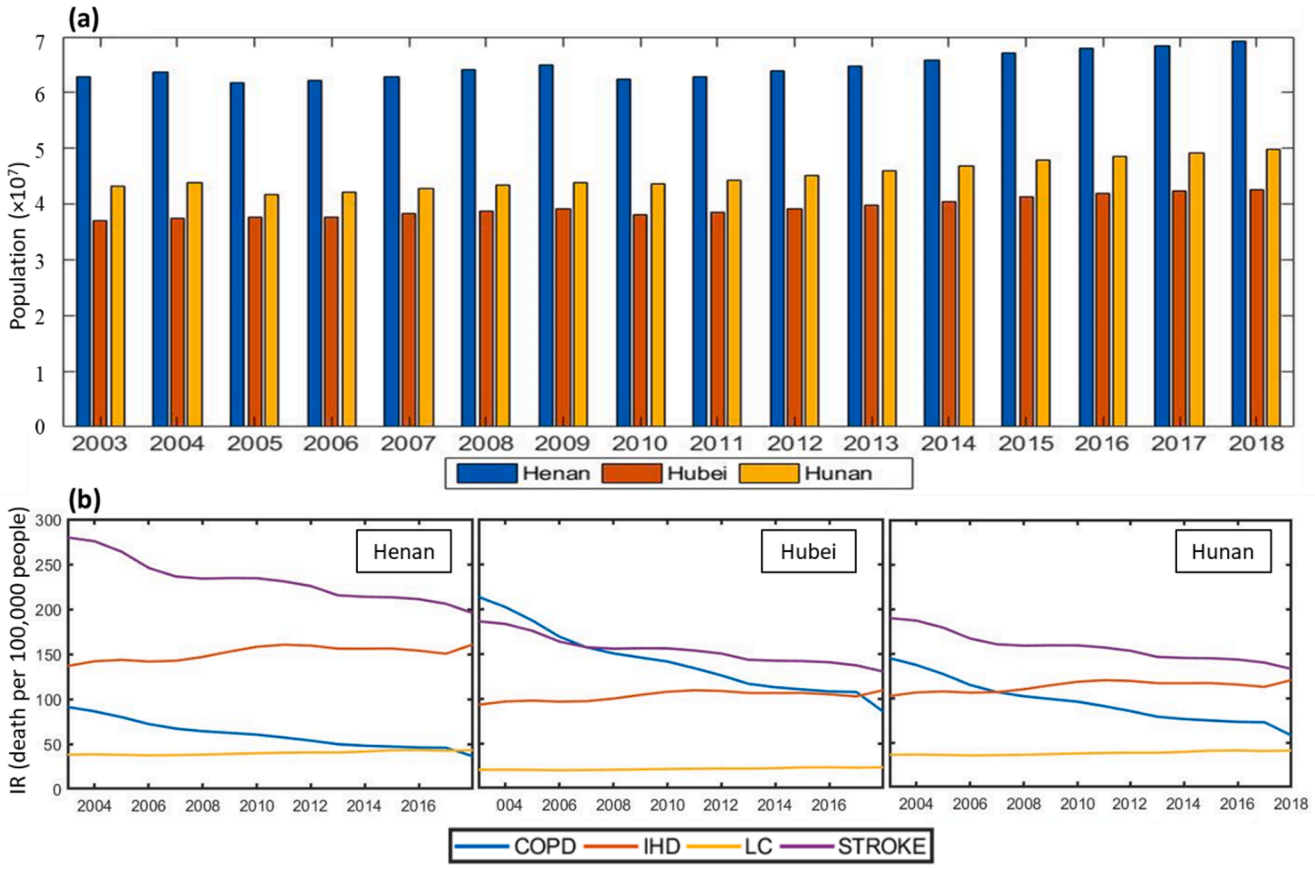

Fig. 2. Time series of (a) population over 25 years old and (b) disease-specific baseline incidence rate in central China from 2003 to 2018.

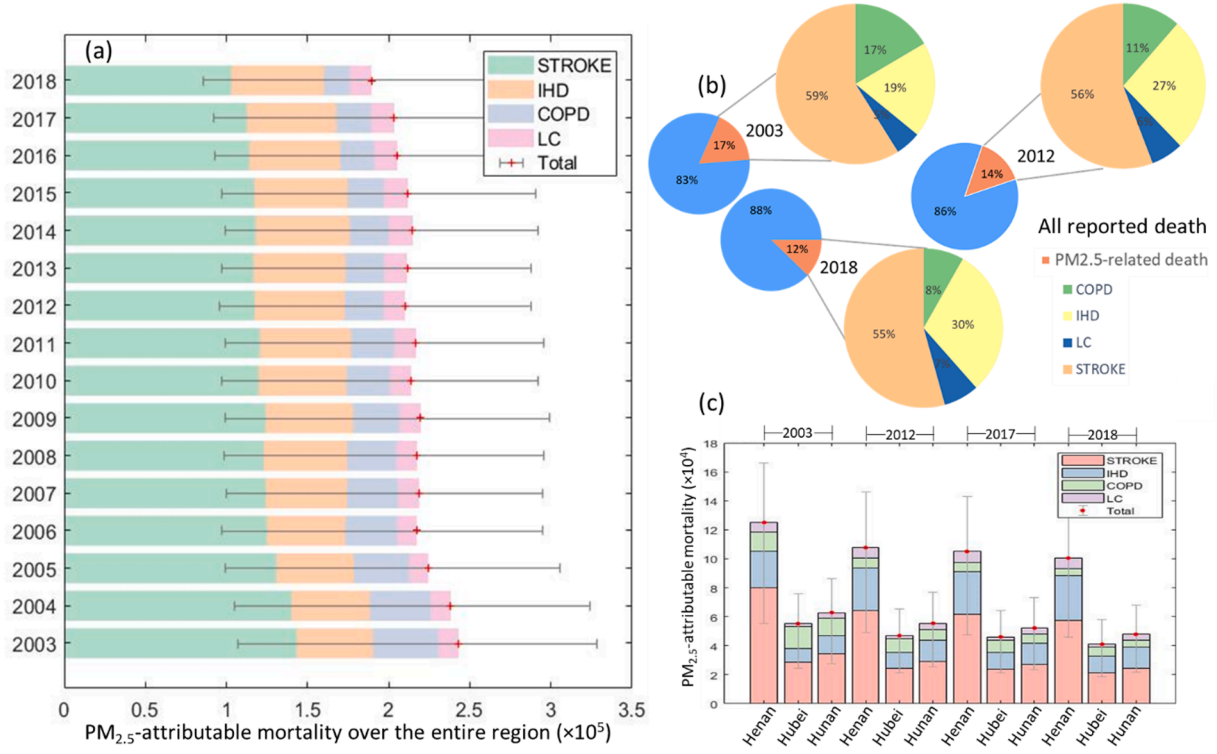

Fig. 3. Annual regional and provincial premature mortalities attributable to $PM_{2.5}$ from 2003 to 2018 in central China. The grey error lines represent the 95% confidence intervals.

decreasing from 59% to 55%; the IHD mortality apparently rose from 47 K to 57 K, accounting for 19% and 30% of total $PM_{2.5}$-attributable mortality in the two respective years; the $PM_{2.5}$-attributable COPD caused 40 K (17%) premature mortalities in central China, which dramatically decreased to 16 K (8%); the LC mortality slightly increased from 13 K (5%) to 14 K (7%); the $PM_{2.5}$-related IHD and LC mortalities did not monotonically increase and had discernable fluctuations (Fig. S9). The primary contribution of the stroke to the total $PM_{2.5}$-attributable premature mortality and its notable decrease was the main reasons causing the total $PM_{2.5}$-attributable mortality decrease over the study period. Focusing on the recent six years when the stricter air pollution intervention policies were implemented, the stroke- and COPD-induced premature mortalities due to $PM_{2.5}$ obviously reduced while the other two disease-specific premature mortalities due to $PM_{2.5}$ changed slightly over the three provinces in 2018 when compared to 2012 (Fig. 3c and Fig. S9). In general, the overall decreasing trend in both mortality values and ratios, especially in the recent six years, indicates the great effectiveness of $PM_{2.5}$-related emission policies that improved health conditions over the study region.

Fig. 4 is an abstract view of city-level adverse health impact induced by $PM_{2.5}$ pollution during the study period. There is a significant variation in $PM_{2.5}$-attributable premature mortality among cities (Fig. 4a). The city-level mortality in Henan tended to be higher than that in the other two southern provinces. The largest long-term mean $PM_{2.5}$-attributable premature mortality concentrated in Henan's cities, including Nanyang (the 16-year mean total mortality was 12 K), Zhoukou (11 K), Zhengzhou (9 K), Shangqiu (9 K), and Zhumadian (8 K), which when combined accounted for ~ 23% of total mortality in the whole central China area. The larger $PM_{2.5}$-attributable premature mortality in these cities was due to the intensive population but not the $PM_{2.5}$ concentration. For example, the highest five mortality cities in Fig. 4 were not ranked as the top in terms of $PM_{2.5}$ level in Fig. 2. The other severely affected cities were Wuhan (in Hubei), Luoyang, and Xinyang (in Henan), with the 16-year mean mortality exceeding 7 K and accounting for ~ 11% of total $PM_{2.5}$-attributable premature mortality in this region. In contrast, the least chronic $PM_{2.5}$-attributable premature mortality numbers were primarily found in Hubei, including Shenlongjia, Ezhou, Qianjiang, and one Hebei city, Jiyuan, which all had an average $PM_{2.5}$-attributable premature mortality<1 K. The lower total mortality in these cities (except Shenlongjia) was mainly associated with the smaller population instead of the pollution levels because the concentration was not low (on average of ~ 60 μg/m^3). Over the four diseases, stroke was the leading lethal factor in all cities over the study region, causing $PM_{2.5}$-attributable premature mortality up to 7 K (equivalently 48.61%~60.88%) on average, while LC led to the smallest number of $PM_{2.5}$-attributable premature mortality, accounting for 3.79%~7.91% of $PM_{2.5}$-attributable premature mortality for each city.

Fig. 4b shows the long-term $PM_{2.5}$-attributable premature mortality reduced from 39 ~ 13,123 in 2003 to 29 ~ 10,538 in 2018 among cities, indicating the risk caused by $PM_{2.5}$ declined throughout the past 16 years. However, the city-level general pattern remained consistent. Cities with higher mortality in 2003 also had a higher number in 2018

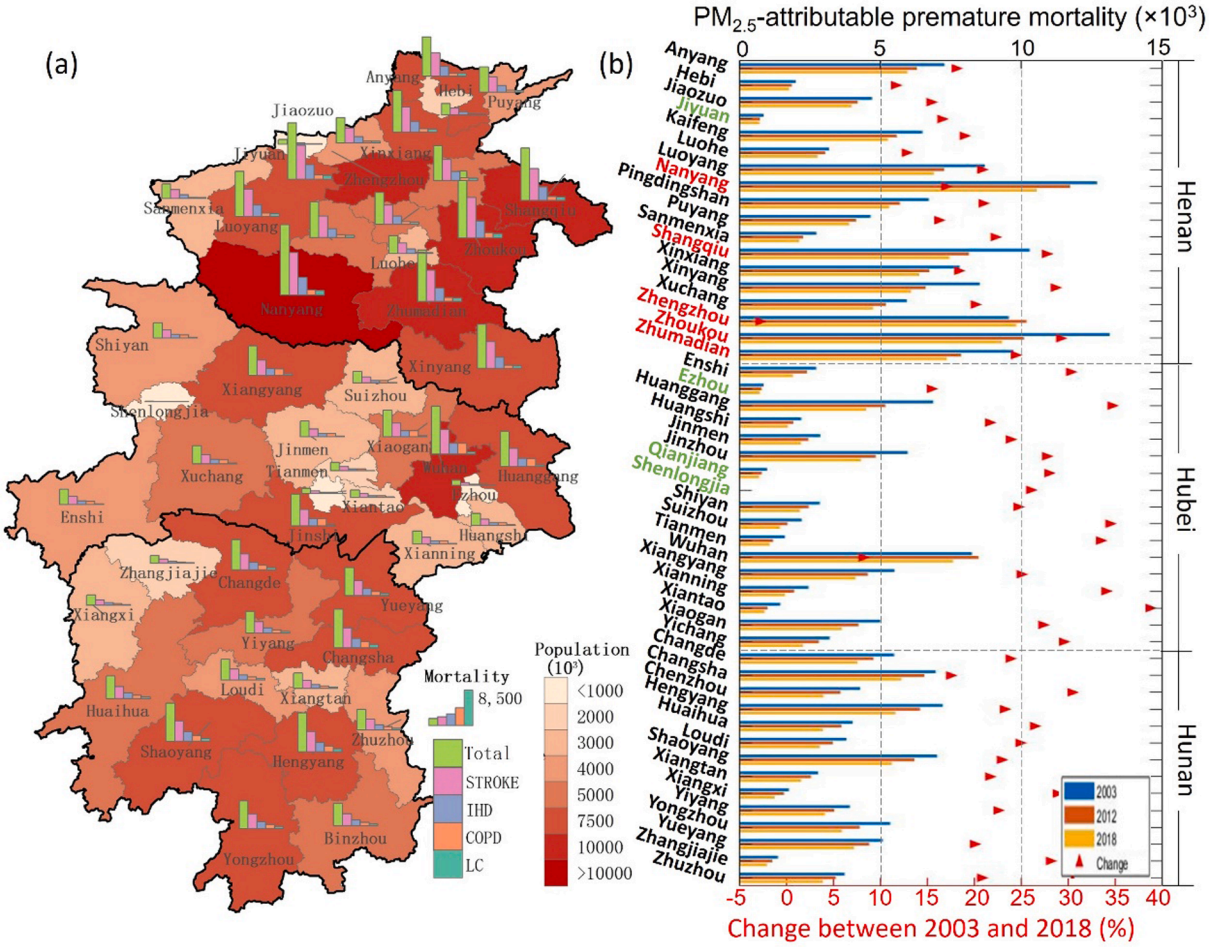

Fig. 4. (a) Spatial distribution and (b) temporal variation of $PM_{2.5}$-attributable premature mortality at a city level in central China between 2003 and 2018. The red and green colors in the city name in Fig. b indicate the cities with the largest and smallest $PM_{2.5}$-attributable premature mortality value over central China, respectively.

despite the obvious reduction in the mortality. The decreasing rate also had significant spatial variations, showing higher in Hubei and Hunan cities. Compared with 2003, the annual decreasing rates in the recent seven years in most cities of Hubei and Hunan provinces were larger than those in the 2003–2012 period.

3.3. Effects of contributing factors

The temporal variation of $PM_{2.5}$-attributable premature mortality is due to the interacted change of the various influence factors. Our health assessment was based on the data of the corresponding year, including $PM_{2.5}$ concentration, population, and baseline incidence rate of individual diseases, to the $PM_{2.5}$-attributable premature mortality change, corresponding to the relative risk caused by $PM_{2.5}$, IR, and POP in Eq. (1), respectively. Use of the data of the corresponding year allowed to comprehensively assess each factor's effect on the estimated $PM_{2.5}$-attributable premature mortality for explaining the trend. Fig. 5 illustrates the changes in each factor to $PM_{2.5}$-attributable individual diseases and total $PM_{2.5}$-attributable premature mortality over individual provinces and over the entire study region. In general, in the absence of changes in population over 25 years old, changes in both $PM_{2.5}$ exposure and incidence rate accounted for a 33.14% decline in total $PM_{2.5}$-related premature mortality between 2003 and 2018 in central China. By contrast, changing population alone resulted in an 11.02% increase in total $PM_{2.5}$-attributable premature mortality in those years, which partially counteracted the decreases driven by changes in population and baseline incidence rate. Comparing effects of individual factors by province, the overall pattern mirrored each other, despite differences in the strength of their effect in the three provinces.

Among contributing factors, changes in incidence rate over the study region were estimated to avoid 58 K $PM_{2.5}$-attributable premature mortality in total and 27 K, 16 K, and 15 K cases in Henan, Hubei, and Hunan, respectively. Changes in $PM_{2.5}$ exposure drove a 7.57%, 9.89%, and 12.74% decline in total $PM_{2.5}$-attributable premature mortality in the three provinces, respectively, and it is the only factor contributing to the decrease for all the four diseases and all of the studied provinces. Demographic changes outweighed the health burden, accounting for 9.18%, 13.36%, and 12.65% increase in total $PM_{2.5}$-attributable premature mortality over the three provinces, respectively.

Among the four diseases, the largest health benefits were observed with the improvement of COPD-related health care, which resulted in a 61.24% decline in $PM_{2.5}$-attributable premature mortality in the study region between 2003 and 2018. Changing the incidence rate of stroke gained health benefits, contributing to a ~ 30% decline in $PM_{2.5}$-attributable premature mortality for the three provinces. Conversely, changes in IHD and LC incidence rates exerted a significant adverse effect on health burden in central China, causing a 17.91% and 12.99% increase in $PM_{2.5}$-attributable premature mortality, respectively.

Before and after implementing the stricter air pollution policies in 2013, changes in $PM_{2.5}$ exposure demonstrated a contrasting effect on changes in $PM_{2.5}$-attributable premature mortality (Fig. 6). Broadly, $PM_{2.5}$ changes in the 2003–2013 period drove the increases in the total $PM_{2.5}$-attributed premature mortality, accounting for 2 K cases in central China. Hunan province was the most affected, with an increased number of 1 K in the period. Specifically, changes in premature mortality due to $PM_{2.5}$ changes between 2003 and 2013 were spatially heterogeneous and varied with diseases. Changing $PM_{2.5}$ concentration also drove small decreases in Hubei for COPD- and LC-induced mortality and in Henan for stroke-induced mortality (Figs. S10 and S11). Conversely, the total $PM_{2.5}$-attributable premature mortality significantly reduced by 22 K between 2013 and 2018, during which $PM_{2.5}$ levels have been declining due to the stringent policies and measures on emission control and air pollutant prevention. The average annual effects between 2003 and 2013 and 2013–2018 further indicated the difference in the impacts of changing $PM_{2.5}$ exposure on health burden before and after the strict clean air actions. In the 2003–2013 period, the annual $PM_{2.5}$-attributable premature mortality over the entire study region increased by 100 cases on average due to the $PM_{2.5}$ changes. In the later period, the $PM_{2.5}$ reduction contributed to an annual average decrease in total mortality of 3 K per year. Changes in total $PM_{2.5}$-attributed incidence rate obviously alleviated the health burden between 2003 and 2013 and 2013–2018, contributing to an annual mean decrease in $PM_{2.5}$-attributable premature mortality of 4 K between 2003 and 2013 and an average decrease of 3 K per year in the 2013–2018 period. The smaller decrease per year in the later period was mainly attributed to the slow decline in stroke and COPD incidence rate in recent years (IHME 2018). Regarding the demographical changes, the total $PM_{2.5}$-attributable premature mortality increased annually by

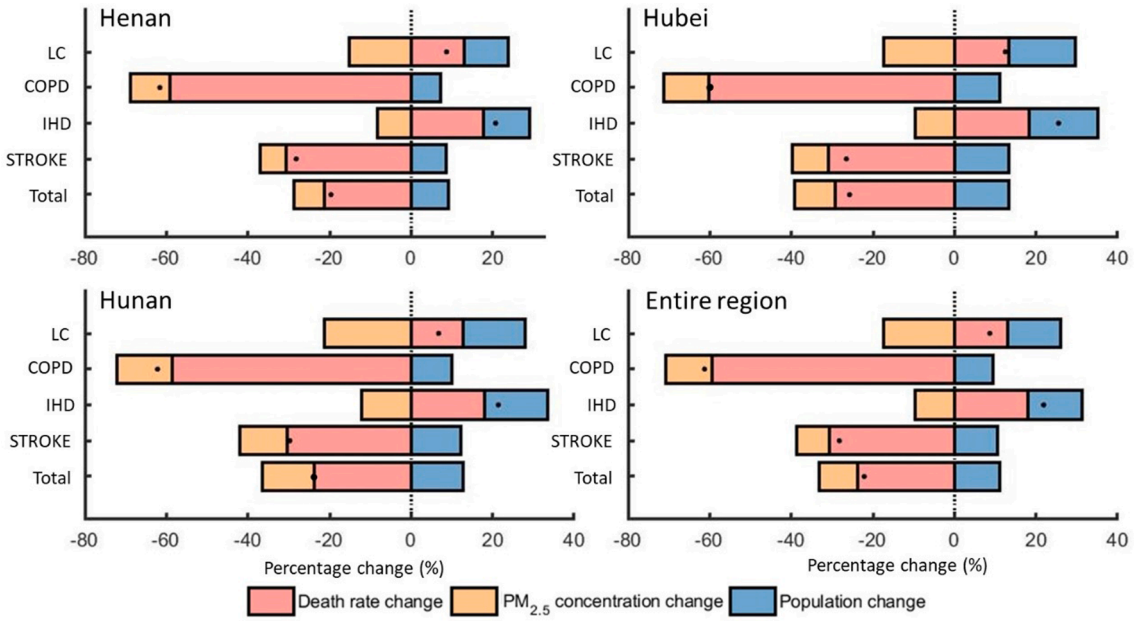

Fig. 5. Percentage change in $PM_{2.5}$-attributable premature mortality at the province level between 2003 and 2018, due to incidence rate change, changes in exposure to $PM_{2.5}$ concentration, and change of population over 25 years old for STROKE, IHD, COPD, and LC. The black dot on each bar demonstrates the overall proportion of changes.

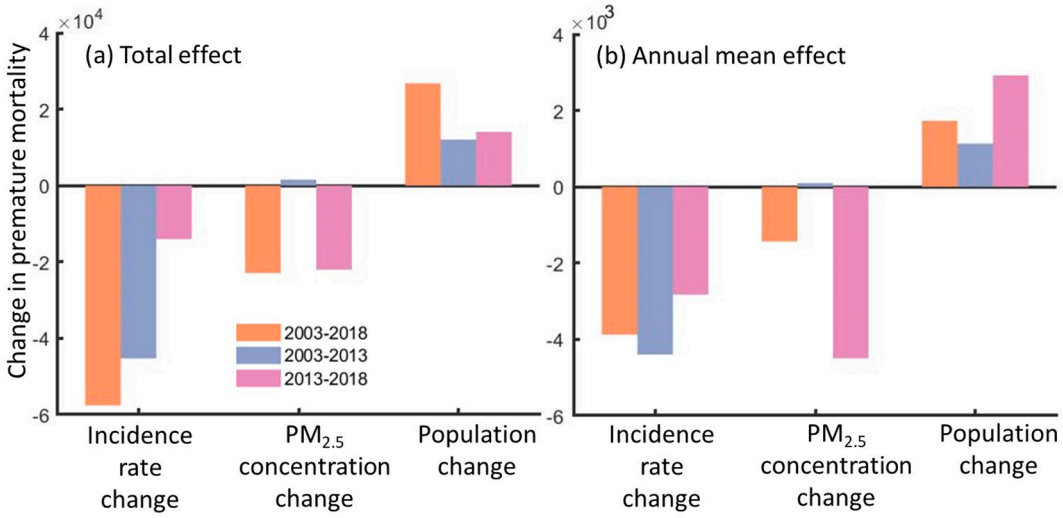

Fig. 6. The changes in $PM_{2.5}$-attributable premature mortality in central China due to different factors in different periods: (a) total and (b) annual average effects.

more than 2 K cases between 2013 and 2018, twice that between 2003 and 2013 because of population growth and aging. The total population and population over 25 years old in central China have almost maintained a steady increasing trend in the past 16 years (Fig. 2a).

Similar decomposition analysis was applied to the changes in disease-specific premature mortality attributable to $PM_{2.5}$ over individual provinces (Figs. S10 and S11). The results demonstrate that the effect of driving factors on the $PM_{2.5}$-attributable premature mortality varied spatially with diseases. The changes in disease-specific mortality due to $PM_{2.5}$ changes over each province in central China in 2003–2013 and 2013–2018 were in line with the findings at a regional scale, meaning that there was a similar sharp contrast in the average effect per year caused by $PM_{2.5}$ changes between the two periods. The changes in incidence rate between 2013 and 2018 led to a larger increase in the LC-induced mortality per year on average compared to those in 2003–2013 period, while the magnitude was smaller for the annual mean IHD-induced premature mortality between the two periods. The effects of demographic changes on the disease-specific mortality in each province over central China in the two periods were consistent with the regional results except changes in COPD mortality in Hubei, where the annual average effect was similar between 2003–2013 and 2013–2018.

4. Discussions

Unlike previous studies reckoning up $PM_{2.5}$-attributed premature mortality at a large spatial scale (e.g., at a regional or provincial level) after the onset of official $PM_{2.5}$ monitoring network (i.e., limited the study period in 2013–2018), this study took advantage of the updated historical high-resolution estimates of $PM_{2.5}$ concentration (He et al. 2020) to assess the variations of health burdens associated with $PM_{2.5}$ exposure over time at a finer spatial scale during a long-term period of 2003–2018. While the spatially or temporally consistent demographical or incidence rate data were used in most previous studies, our study employed the higher-spatiotemporal-resolution and more-relevant data, i.e., year-to-year population distribution and provincial incidence rate data. The added spatiotemporal richness allowed us to quantitatively decompose the effects of changes in influencing factors, helping us to pinpoint the relevant driving force in the $PM_{2.5}$-attributable health burden in central China, e.g., related to changes in healthcare variation, population migration/growth, and the $PM_{2.5}$ pollution variations driven by emission control policies. Significant new information was brought to light, which enriches the understanding of the change in $PM_{2.5}$-related health risk to the public, not only helping guide the future air quality policymaking but also advancing the epidemiological study over central China and even the entire country.

Compared with previous studies, our results demonstrate that $PM_{2.5}$-attributable premature mortality in central China continued to decrease since 2003, especially after implementing stricter air pollution policies in 2013. The magnitude and the downward tendency of the resultant mortality in this study were similar to previous research (Lu et al. 2019; Wang et al. 2018; Zou et al. 2019). Specifically, the average $PM_{2.5}$-attributable premature mortalities in Henan, Hubei, and Hunan between 2001 and 2017 as calculated by Lu et al. (2019) were 124,800, 593,00, and 61,100, respectively, and a decreasing trend in $PM_{2.5}$-attributable premature mortality was also observed during the last five years; likewise, the number provided by Zou et al. (2019) was 105,906 over Henan in 2013 and the value reduced by ~ 7,000 in 2017. Although those studies identified the decreasing trend in $PM_{2.5}$ pollution and $PM_{2.5}$-attributable premature mortality, using the total variation in mortality can neither directly interpret the effect of alleviating air pollution on health burden nor assess whether the current air pollution policies are sufficient to benefit the future public health. This is because $PM_{2.5}$-attributable premature mortality is affected by many factors that may impose confounding effects. Our decomposition analysis provides a reliable approach to quantify the effects of changes in these confounding factors. In addition, the high-resolution estimates of $PM_{2.5}$ concentration used in this study help improve the spatial scale of $PM_{2.5}$-related premature mortality in central China. Compared with previous studies that employed coarse-resolution data, e.g., 10 km and coarser (Liu et al. 2016; Liu et al. 2017; Wang et al. 2018), the uncertainty originated from the spatial resolution of the data in $PM_{2.5}$-attributable premature mortality estimation could be theoretically reduced in this study. We also calculated the $PM_{2.5}$-attributable premature mortality using coarse-resolution data and compared the coarse-resolution results with those based on the fine-resolution data. The comparison results in Fig. S12 indicate that the coarse-resolution data probably underestimated the premature mortality caused by $PM_{2.5}$ exposure.

The long-term variation in regional $PM_{2.5}$-attributable premature mortality integrates the intersection of three driving factors: air quality change, demographic change, and incidence rate change. In terms of air quality, the average concentration of $PM_{2.5}$ over central China experienced a slight decrease since 2007 due to the implementation of national emission control measures such as the use of de-sulfured equipment in the industry in 2006 (Lu et al. 2010; Ma et al. 2019). Following the stringent national measures on air quality since 2013, the provincial governments in central China also took a series of clean air actions. For example, Henan enacted the "Three Action Year Plan to battle against air pollution," which aimed to reduce the provincial levels of $PM_{2.5}$ to

lower than 58 μg/m^3 in 2020 (http://www.henan.gov.cn/2018/09–21/692225.html). As a consequence, regional $PM_{2.5}$ pollution levels reduced significantly, which was in line with the national tendency (Lin et al. 2018; Ma et al. 2019; Xue et al. 2019b). Benefiting from those air quality regulations, the risk in exposure to $PM_{2.5}$ obviously reduced in the study region, especially in recent five years, contributing to 22 K fewer $PM_{2.5}$-attributable premature mortalities in 2018 compared to 2013. It should be noted that ~ 0.6 K more $PM_{2.5}$-attributable premature mortality was observed due to the changes in exposure to $PM_{2.5}$ between 2016 and 2017, showing a positive effect. The increase was relatively minor, but it implies that the changes in $PM_{2.5}$, even in implementing the stricter control policies, were insufficient to alleviate the health burden. These findings suggest that the efforts on air quality improvement have been evidenced effective to decrease the associated health burden; nevertheless, these efforts need to maintain and even strengthen to continue the decreasing trend in future $PM_{2.5}$-attributable premature mortality. For example, enhancing regulation and management schemes on replacing traditional fossil fuel combustion with clean energy in industry and central heating may be an option, which also corresponds to the country's plan to reduce CO_2 emissions to achieve carbon neutrality.

The positive effect driven by the $PM_{2.5}$ reduction was offset by demographic change in the long-term period of 2003–2018. Focusing on the recent six years, the positive effect of $PM_{2.5}$ reduction was larger than the negative effect of population change. However, we cannot conclude that the situation has improved because the annual average of population-induced negative effects in 2013–2018 doubled in 2003–2013. The population growth with age structure change was one reason to cause $PM_{2.5}$-attributable premature mortality in the past 16 years. Due to the growth in the proportion of those over 25 years old to the total population, the number of 25 + population consistently increased in the three provinces over central China (Fig. 2a), which led to an increase in $PM_{2.5}$-attributable premature mortality for this region. In addition, the countervailing effect of population change may be partly attributable to the internal population mobility driven by urbanization (rural–urban migration). The inner migration caused by the rapid development and urbanization prompted the population to move to urban areas. Unfortunately, the air pollution issue in those urban regions was inclined to be severer. The rural–urban migration drove more residents exposed to a higher level of $PM_{2.5}$ pollution, which would consequently intensify the $PM_{2.5}$-attributed health burden. To alleviate the health damage, it is worth seeking for optimizing population distribution policy and planning. For instance, effective urban planning may be in need to guide residential communities living away from the downtown areas that tend to be more polluted. Besides, promoting $PM_{2.5}$ pollution forecasting technology and advising the public to reduce outdoor activities or wear masks during heavy pollution events may lower individual exposure levels.

The incidence rate contributed to the most reduction in the $PM_{2.5}$-attributed premature mortality between 2003 and 2018, accounting for 23.70% of the decreasing health burden over central China. Without any doubt, the economic development in China during the past several decades has continued to promote health and medical condition to an advanced level. The improvement in health condition therefore lowered down the baseline incidence rate for the total $PM_{2.5}$-attributable premature mortality. Nevertheless, the incidence rate for individual diseases had a complicated effect on changes in $PM_{2.5}$-attributable premature mortality: changes in stroke and COPD incidence rates and changes in IHD and LC incidence rates demonstrated a countervailing effect on the number of $PM_{2.5}$-attributable premature mortality over central China. The increasing trend in the annual baseline incidence rates of IHD and LC (Fig. 2(b)) caused a negative effect related to the two diseases. These opposite tendencies shown by IHD and LC incidence were probably attributed to changes in lifestyle and their major risk factors. Associated with urban development, China's standard of living and lifestyle has experienced tremendous changes over the past decades. In recent decades, an increasing trend in diets with higher fat, higher blood lipids, and higher blood sugar has been observed (Wan et al. 2017). Because hypertension, diabetes, and hypercholesterolemia are regarded as the leading risk factors for IHD (Hata and Kiyohara 2013), the unfavorable lifestyle and dietary changes would increase the IHD burden. For example, previous studies have shown a positive relationship between serum cholesterol level and IHD-induced mortality (Critchley et al. 2004; Wan et al. 2017). To convert the increasing trend in IHD incidence rate, promoting a healthier lifestyle such as increasing the proportion of cereals in the diet may be helpful. For LC burden, the incidence is primarily associated with smoking and air pollution (Yim et al., 2022). Previous studies revealed that smoking other than air pollution might be the primary factor leading to the most premature deaths (Gao et al. 2020). Our decomposition results support this finding because an increase in LC incidence rate resulted in more health burden despite declining $PM_{2.5}$. Therefore, widespread cessation and screening measures on smoking would help improve the lung cancer incidence and further reduce the LC-induced mortality.

Significant spatiotemporal variations in $PM_{2.5}$-attributable premature mortality (Fig. 3 and Fig. 4) were observed, resulting from the combined effects of air quality, population, and incidence of diseases. Because the three driving forces are associated with many factors, e.g., air pollution policies, demographic distribution, growth, and structure, rural–urban migration, medical condition, diversity in lifestyles, and disparity in socioeconomic development, combined measures and regulations should be taken to alleviate the health burden due to $PM_{2.5}$. We note that it is unnecessary or difficult to change the natural growth in population and aging compared with other factors. Thus, regulation and management regarding $PM_{2.5}$ pollution abatement, health advisory, and medical condition improvement should be strengthened. To cope with the spatiotemporal dynamics in premature mortality induced by $PM_{2.5}$ exposure, the joint effect of $PM_{2.5}$ pollution mitigation and health improvement policies should not be overlooked. In addition, the collaboration between cities may be in need because the premature mortality due to air pollution could be partly affected by transboundary air pollution (Gu and Yim 2016; Hou et al. 2019; Shi et al. 2020; Yim et al. 2019a; Yim et al. 2019b) and population migration (Shen 2015; Shen and Liu 2016).

Despite improved accuracy of mortality estimates and being informative for policymaking, this study has several uncertainties and limitations, including satellite-retrieved $PM_{2.5}$ dataset, the population distribution and age structure data, the incidence rate, and the relative risk. Due to the lack of historical $PM_{2.5}$ observations, the relationship between ground $PM_{2.5}$ and satellite AOD preceding 2013 cannot be quantified directly, probably biasing historical predictions of $PM_{2.5}$. To validate our long-term $PM_{2.5}$ predictions, we used the state-of-the-art approach, i.e., annually iterated cross validation, to evaluate the predictive power for the estimates outside the observation years and compared with previously reported coarse-resolution data (He et al. 2020). The validation and comparison results demonstrate an overall good agreement between our estimates and concentration from monitoring sites or previous research (Fig. S2 and Table S2). In terms of population and age structure data, we applied the distribution for the total population times the ratio of over 25 years old to offer the population value over each grid cell because it is impossible to obtain the geographical data of population over 25 years old. Due to the lack of detailed age ratio data for each province or city, we used the ratio for the entire of China instead, potentially biasing the mortality estimation because the ratio may vary from one province to another. In addition, it has to be acknowledged that, while the annual population data used to estimate long-term health impacts generate acceptable estimates for each year in the study period, the population mobility within one year may influence the accuracy of the health estimates. Although previous studies based on monthly population distribution data found only a slight impact on long-term $PM_{2.5}$ exposure and mortality estimation (He et al. 2021; Song et al. 2019), uncertainty related to time-activity patterns of population in health burden needs to be further examined.

Another limitation that may cause uncertainty in our health impact estimation is the assumption in baseline incidence rate. The original annual data of all of China were derived from the GBD dataset (IHME 2018), and the provincial values between 2003 and 2018 were projected using the provincial baseline incidence rate of China in 2013 reported by the GBD study (Zhou et al. 2016). Thus, it assumed that the baseline incidence rate remained consistent within a province and that the changing rate of baseline incidence rate for each province kept invariant temporally. Although the projection method was acceptable and applied in numerous previous studies (Lu et al. 2019; Wang et al. 2018; Zou et al. 2019), the assumption may introduce uncertainty because the baseline incidence rate, as well as the changing rate, can be different from city to city in the realistic world. In addition, the exposure–response function would introduce uncertainty in mortality estimates. In this study, we adopted the widely used exposure–response function, i.e., the IER model by Burnett et al. (2014), to estimate the relative risk related to $PM_{2.5}$ and obtained comparable mortality estimates across studies. To identify the impact of various exposure–response functions on contributing factor analysis, we also used another exposure–response function, i.e., the global exposure mortality model (GEMM) (Burnett et al. 2018), to conduct the $PM_{2.5}$-related mortality estimation and decomposition analysis (Figs. S13 and S15). We held other inputs unchangingly to ensure comparability between mortality results derived from the two exposure–response functions. Through comparing Figs. S13- S15, and Figs. 3-6, we found that the GEMM-based mortality estimates were larger than those derived from the IER model, but the relative contribution pattern regarding the three factors did not apparently change, which implies that the core conclusion made by this study still holds.

5. Conclusions

This study investigated the spatiotemporal dynamics in premature mortality attributable to ambient $PM_{2.5}$ pollution in central China from 2003 to 2018 and further separated the relative effect of driving factors using state-of-the-art data. Throughout the study period, significant spatiotemporal variations were observed in $PM_{2.5}$-attributed health impact over central China. Henan province had the largest number of chronic $PM_{2.5}$-attributable premature mortality, while the smallest number was primarily observed in Hubei province. The overall $PM_{2.5}$-attributable premature mortality in central China decreased from 2003 to 2018, and the decline speeded up with the significant $PM_{2.5}$ reduction since 2013. The clean air actions implemented in recent years alleviated the associated health burden, converting the negative contribution induced by $PM_{2.5}$ changes during 2003–2012 to positive in 2013–2018. The change in baseline incidence rate brought the largest reduction in premature mortality due to $PM_{2.5}$, but changes in IHD and LC aggravated the health burden. Population changes and aging resulted in the increase in total $PM_{2.5}$-attributable premature mortality in the study years, which partially counteracted the decreases driven by changes in the other two factors. Our findings suggest that air pollution intervention measures need to maintain and even to be more stringent to continue the decreasing trend in future health burden due to $PM_{2.5}$. A more dynamic and comprehensive strategy should be formulated and implemented to tailor the spatiotemporal heterogeneity in $PM_{2.5}$-attributed health impact. Besides, combined actions across the provincial and city-level administrative borders are needed for future improvement on $PM_{2.5}$-attributed health risk because of transboundary air pollution and human mobility. The mortality and decomposition methods could be applied to other regions and countries, and the relevant results and findings allow cross-boundary connections and comparisons to benefit public health worldwide.

CRediT authorship contribution statement

Qingqing He: Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Yefu Gu:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Steve Hung Lam Yim:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Vice-Chancellor's Discretionary Fund of The Chinese University of Hong Kong (Grant No. 4930744), Dr. Stanley Ho Medicine Development Foundation (Grant No. 8305509), and the National Natural Science Foundation of China (Grant No. 41901324).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107110.

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