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Assessing the evolution of $PM_{2.5}$ and related health impacts resulting from air quality policies in China

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ABSTRACT

Air pollution represents one of the world's largest environmental health risks. Following China's promulgation of a series of harsh clean air policies, the long-term evolution of its air pollution and the effects of policies implemented were assessed. The 3D spatio-temporal dynamic evolution characteristics of $PM_{2.5}$ concentrations in China were analyzed based on pixel and urban-scale $PM_{2.5}$ annual mean concentration datasets from 2000 to 2019 and using emerging spatial and temporal hot spots. The reduction of premature deaths affected by environmental policies at the city scale was estimated using improved health effect assessment methods. The results show that: 1) The evolution trend of the average $PM_{2.5}$ concentration in China from 2000 to 2019 follows an "M" shape; the year 2013 was an important turning point marking a significant decline in $PM_{2.5}$ concentrations. 2) $PM_{2.5}$ concentrations east of Hu's line showed a decreasing trend during the period 2013–2019. Although urban agglomerations are areas of severe air pollution, in recent years they showed the best control effects. 3) The proportion of population, land, and cities exposed to $PM_{2.5} > 35\mu g/m^3$ decreased by 27.98%, 13.50%, and 29.15%, respectively, during 2013–2019. 4) As a result of air quality policies, annual deaths attributable to $PM_{2.5}$ pollution in 2019 decreased by 177 thousand (14.75%). This study contributes to the formulation of China's policies and action plans for pollution abatement and also provides insights and methods that could be applied to other countries.

1. Introduction

Air pollution has manifold effects on health, ecosystems, tourism, and climate (Manisalidis et al., 2020; Wang et al., 2021b). It has also been identified as a global health priority in the Sustainable Development Goals (SDGs) regarding health (Goal 3), cities (Goal 11), and energy (Goal 7) (Sachs et al., 2019). Air pollution represents the biggest environmental risk to health (Cohen et al., 2017). A positive significant association was reported between air pollution and mortality and welfare costs (Owusu and Sarkodie, 2020). Globally, 8.42 million deaths were attributable to ambient $PM_{2.5}$ in 2016 (Yin et al., 2020a). Air pollution has also been linked to a large increase in COVID-19 infection and mortality rates (Travaglio et al., 2021). Air pollution issues in China began to become evident in the early 21st century, resulting from the rapid industrialization and urbanization that followed the adoption of reforms and opening-up policies. In the last ten years, air pollution has caused wide concerns in China. In 2017 alone, 1.24 million deaths in China were attributable to air pollution (Yin et al., 2020b). The economic loss due to $PM_{2.5}$ exposure has been estimated at 101.39 billion US$, about 0.91% of the total Chinese GDP (Maji et al., 2018b). Chinese Premier Li Keqiang declared a "war against pollution" in 2014. In spite of the government's efforts, air pollution in China is still serious. The mean $PM_{2.5}$ concentration in the first half of 2021 was 34 $\mu g/m^3$ (the World Health Organization (WHO) guideline suggests that $PM_{2.5}$ should not exceed 5 $\mu g/m^3$ annual mean). Therefore, it is necessary to review the long-term evolution of air pollution in China and the effect of policies implemented to better formulate new plans and policies for the future.

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Interventions and policies for tackling air pollution in China started in the 1990s. Emission controls of SO_2 and clean coal combustion solved acid rain issues around 2007 (Larssen et al., 2006). Around 2013, following several heavy pollution events, high levels of haze and $PM_{2.5}$ were widely reported by the media and attracted unprecedented attention from the government and the public. That triggered the promulgation of a series of harsh clean air policies especially aiming at particulate matter ($PM_{2.5}$ and PM_{10}). Control actions on multiple precursors and sectors have targeted the reduction of PM concentrations, marking a transition to an air-quality-oriented strategy (Lu et al., 2020). Two significant government action plans were released in 2013 and 2018: the Air Pollution Prevention and Control Action Plan (Air Plan A) and the Three-year Action Plan for Cleaner Air (Air Plan B), respectively. The two plans set the roadmap across all key sectors for air pollution control to reduce the emissions of major air pollutants and decrease the number of days with high air pollution (Cai et al., 2017, Lu et al., 2020). In particular, the prevention and control of air pollution in autumn and winter has been strengthened in the Jing-Jin-Ji Region, the Yangtze River Delta, and the Fenwei Plain. Now that the implementation period of these two policies has come to an end, it is time to ask the following questions: How much did they contribute to the improvement of China's air quality? How much has air quality improved in different regions in recent years? What are the health benefits of these environmental policies that came at a great economic cost?

A growing number of studies has concentrated on the spatial and temporal patterns and characteristics of air pollution in China (Fan et al., 2020; Fang et al., 2015; Liu et al., 2017; Lu et al., 2017), especially in urban agglomerations with serious environmental issues, like the Beijing-Tianjin-Hebei Region (Du et al., 2019; Wang et al., 2020), the Yangtze River Delta (Ma et al., 2019; Yang et al., 2019), and Central China (Li et al., 2020). $PM_{2.5}$ is the most commonly used proxy indicator of exposure to air pollution (Xiao et al., 2020; Zhao et al., 2019; Zhou et al., 2019). Spatial analysis methods including Moran's I (Ding et al., 2019), Getis-Ord Gi* (Ye et al., 2018), and Standard Deviational Ellipse (He et al., 2021) have been used to analyze the spatial characteristics (agglomeration and hot spots) of air pollution. Using remote sensing data or monitoring sites data, the yearly and seasonal trends of various air pollutants in China were detected (He et al., 2021, Kou et al., 2021, Maji and Sarkar, 2020). From 1998 to 2017, China's environmental risks have been alleviated as a whole (Du et al., 2020). However, limited by data duration, these analyses have been rarely combined with their policy background. Moreover, most of the previous spatial pattern analyses have been simple and have not mined the spatio-temporal dynamic characteristics at a fine scale.

Policy initiatives and intervention programs that address air pollution generate a range of human health benefits (WHO, 2016), and China's progress on pollution control is currently unfolding (Geng et al., 2021; Tilt, 2019; Yan et al., 2021; Zhang et al., 2021). Some scholars have analyzed the effectiveness of Air Plan A on air quality improvements and health benefits from 2013 to 2017 in China (Feng et al., 2019; Huang et al., 2018; Xue et al., 2019; Yue et al., 2020). Wang et al. (2021a) measured the health risk of $PM_{2.5}$ and O_3 exposure in China during 2013–2018. Fan et al. (2020) reported that 78% and 89% of stations showed decreasing PM_{10} and $PM_{2.5}$ during 2014–2018. Luo et al. (2020) calculated the health impacts and economic benefits of $PM_{2.5}$ concentration reduction during 2016–2018. Du and Li (2020) assessed the effects of environmental regulations on pollution abatement and collaborative emissions reduction from a micro-perspective. Air pollution prevention and control under collaborative policies in a heavily polluted area (e.g., the Jing-Jin-Ji Region) is conducive to further improving regional air quality (Song et al., 2020; Wu et al., 2021; Xu et al., 2021). However, these studies estimated premature deaths mostly on a national scale, and there is remarkably little work at city scales. Moreover, previous assessments of the health effects of policies on $PM_{2.5}$ exposure only compared the two years before and after their implementation, likely resulting in underestimates.

Considering these two limitations of past research, in this paper remote sensing and air quality monitoring data were integrated to form pixel-scale and urban-scale $PM_{2.5}$ annual mean concentration datasets from 2000 to 2019. Then, using emerging spatial and temporal hot spots, the 3D spatio-temporal dynamic evolution characteristics of $PM_{2.5}$ concentration in China over the past 20 years were analyzed. The population proportion, land proportion, and city proportion under different concentrations of $PM_{2.5}$ exposure were thus calculated. Finally, based on improved health effect assessment methods, we estimated the reduction of premature deaths in each city affected by environmental policies. By evaluating the effect of air pollution control from multiple dimensions at grid and city scales, we aimed to identify key areas for preventing and controlling air pollution and understand the effectiveness of past policies. This study not only contributes to the formulation of China's approach for pollution abatement but also provides insights and methods that could be applied to other countries.

2. Data and methods

2.1. Data preparation and preprocessing

This study covers the period from 2000 to 2019. The year 2020 was ruled out because China's travel restrictions policies during the COVID-19 pandemic led to a sizeable improvement in air quality (He et al., 2020; Wang and Su, 2020). China's population raster data for the period 2000–2019 were derived from LandScan™ (https://landscan.ornl.gov), which is a global population distribution dataset at approximately 1-km ($30'' \times 30''$) spatial resolution derived using best available demographic (Census) and geographic data, remote sensing, and image analysis techniques. As one of the most accurate global population gridded dataset, it has been widely used and even regarded as the "ground truth" of population distribution (Bhaduri et al., 2007; Calka and Bielecka, 2019). GDP density raster data were derived from National Earth System Science Data Center, National Science & Technology Infrastructure of China (http://www.geodata.cn). Annual datasets of $PM_{2.5}$ concentration in China from 1998 to 2018 were obtained from the Atmospheric Composition Analysis Group (http://fizz.phys.dal.ca/~atmos/martin/?page_id=140). Using advances in satellite observations, chemical transport modeling, and ground-based monitoring, the datasets have the advantages of high spatial resolution (0.01°), wide coverage, high accuracy, and long-term stability (Hammer et al., 2020; Ravishankara et al., 2020). The $PM_{2.5}$ raster data for 2019 is based on the annual mean $PM_{2.5}$ concentration of 1509 environmental monitoring stations across China using kriging interpolation. These monitoring data come from the China National Environmental Monitoring Center (http://www.cnemc.cn/). In addition, the map of administrative divisions was obtained from the Ministry of Natural Resources of China, and the scope of municipal districts was based on the 2019 administrative divisions.

2.2. Analysis of emerging spatial and temporal hot spots based on the space-time cube

As a spatio-temporal data model and visualization method, a space-time cube (STC) can integrate the spatial, temporal, and attribute information of geographic phenomena, and realize the historical reconstruction, spatio-temporal change tracking, and trend prediction of data. A 3D cube is made up of space-time bins, and every bin has a fixed position in space (x, y) and in time (t). Bins covering the same (x, y) area share the same location ID. Bins encompassing the same duration share the same time-step ID. The count value for each bin reflects the number of events or records that occurred at that location over a time-step interval (Fig. 1a). In this research, the STC and spatio-temporal hot spot methods were combined to intuitively reflect the spatial distribution and temporal changes of $PM_{2.5}$ concentrations to reveal the spatio-temporal characteristics and evolution patterns of China's $PM_{2.5}$ concentration. We used Esri's ArcGIS Pro 2.7 software to implement our analysis.

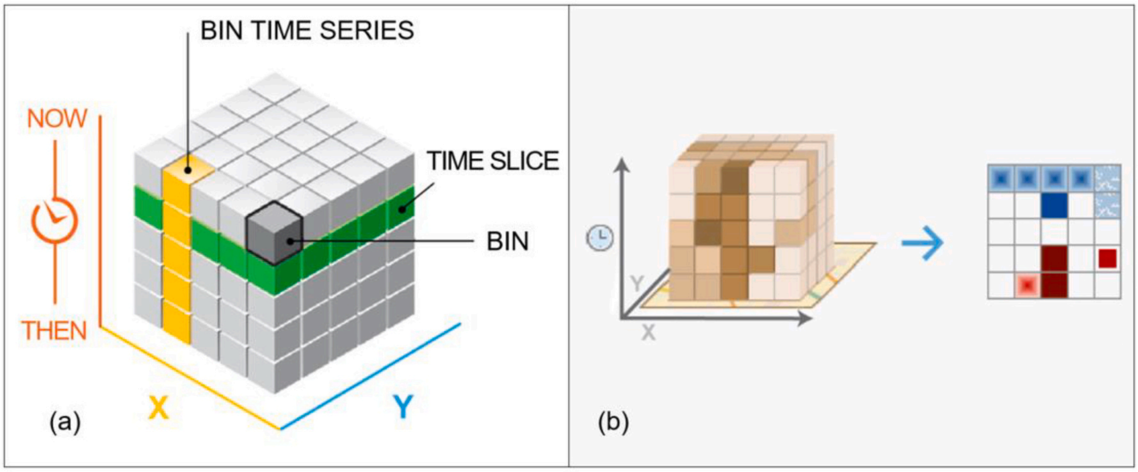

Fig. 1. Structure of the space-time cube (http://pro.arcgis.com). (a) Space-time bins in 3D; (b) Generated bins in 2D for the emerging hot spot analysis.

First, the spatiotemporal information on $PM_{2.5}$ data was aggregated into the spatiotemporal bins and generated a special data structure named NetCDF in STC. In this study, a total of 1222 spatial bins were generated by the STC model, each of which is a 1° square (about 111 km × 111 km). A total of 24,440 bins with a yearly time interval were generated to capture the interannual variation of $PM_{2.5}$ over 20 years.

Second, we detected the spatial and temporal hot spots based on the created space-time bins using ArcGIS Pro 2.7. This approach can find new, intensifying, diminishing, and sporadic hot and cold spots. Based on Getis-Ord G_i^* (Getis and Ord, 1992), the neighborhood distance and time step were set to identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots). This created a new output feature class with a z-score and *p*-value. Then, the Mann-Kendall trend test was used to assess the trend of hot and cold spots (Hamed, 2009). By comparing the z-score and p-value of the space-time bar, each location was classified into a different space-time pattern. We can visualize these patterns in 2D or 3D (Fig. 1b). On a 2D map, each location may be one of 17 categories (8 hot spots, 8 cold spots, and 1 undetected pattern), depending on the temporal and spatial evolution trends. See the ESRI manual for a description of each model (ESRI, 2021).

2.3. *Estimating the premature deaths from ambient $PM_{2.5}$ exposure*

Research has shown that premature mortality is attributable to ambient $PM_{2.5}$ for five major disease endpoints. These endpoints are ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), lung cancer (LC), acute lower respiratory infection (ALRI), and cerebrovascular disease (STR) (Apte et al., 2015; Collaborators and Ärnlöv, 2020). In this study, the number of premature deaths caused by these five diseases was selected as the health effect. The number of premature deaths attributed to $PM_{2.5}$ exposure was calculated based on the Integrated Exposure-response (IER) model (Burnett et al., 2014). This model was first proposed in the Global Burden of Disease 2010 report (Lim et al., 2012), and has been widely applied in health effect studies (Lelieveld et al., 2015; Maji et al., 2018a). The formula is as follows:

$$M_i = Y_i \times Pop \times (RR_i - 1)/RR_i \qquad (1)$$

where M_i represents premature deaths attributable to disease *i*, and Y_i represents the baseline mortality from the disease *i* (Table 1), which were collected from *China Surveillance Data for Cause-of-death 2019* and *China Health Statistical Yearbook 2020* (China, 2020a, 2020b); *Pop* is the exposed population; RR_i represents the relative risk value for disease *i*, which is referred from the IER Lookup Table (Apte et al., 2015). This

Table 1
Baseline mortality from five diseases in 2019.

Type of disease	Baseline mortality (ppm)
Ischemic heart disease (IHD)	12.823
Chronic obstructive pulmonary disease (COPD)	5.268
Lung cancer (LC)	4.748
Acute lower respiratory infection (ALRI)	0.022
Cerebrovascular disease (STR)	0.505

table provides the relative risk values for the above five diseases at different $PM_{2.5}$ exposure levels and has been widely used to estimate various types of health risks caused by $PM_{2.5}$ pollution (Brauer et al., 2016, Cohen et al., 2017). The premature deaths from the five diseases were added together to derive the total number of deaths attributed to ambient $PM_{2.5}$ exposure.

2.4. *Impact assessment of environmental policies*

Previous studies of the impact of policies on deaths from $PM_{2.5}$ exposure have only compared deaths in the two years before and after the implementation of policies. This paper proposes a new calculation method to evaluate the health effects of policies more scientifically. First, it assumes a no-policy scenario (counterfactual thinking), in which no new environmental policies have been released since 2013. Based on the historical trend (2000–2013) of $PM_{2.5}$ concentrations in each city, a linear regression was established to calculate the $PM_{2.5}$ concentration of each city in 2019 without the influence of policies. Second, premature deaths were calculated based on the actual scenario and the no-policy

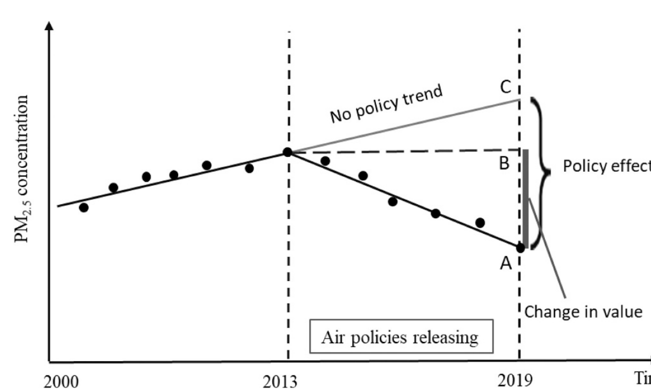

Fig. 2. Schematic diagram of a policy effect assessment.

scenario, respectively. As shown in Fig. 2, we believe that the difference between the two scenarios (C-A) is the health effect of the environmental policies. This idea is different from previous studies, which calculated B-A as a policy effect.

3. Results

3.1. Temporal evolution characteristics of $PM_{2.5}$ concentrations

First, we calculated the annual mean $PM_{2.5}$ concentration of 343 Chinese cities based on the $PM_{2.5}$ raster data in the municipal areas. Fig. 3 illustrates the average $PM_{2.5}$ concentration of all Chinese cities from 2000 to 2019. The overall evolution trend follows an "M" shape, which can be divided into three developmental stages. In the first stage (2000–2007), the annual mean of urban $PM_{2.5}$ concentration had a significant upward trend, rising from 36.87 μg/m^3 in 2000 to 49.13 μg/m^3 in 2007, with an average annual increase of 1.75 μg/m^3. In the second stage (2007–2012), the annual mean of urban $PM_{2.5}$ concentration presented a slowly decreasing trend in fluctuation, and the concentration was 45.64 μg/m^3 in 2012. This could be due to the fact that, on the one hand, since 2007, China has advocated for "ecological civilization" and paid attention to the prevention and control of environmental pollution. On the other hand, meteorological conditions in these years have facilitated the diffusion of particulate matter (Chen et al., 2020; Xu et al., 2020). In February 2012, China set the first ambient $PM_{2.5}$ concentration standards and the concentration limit of $PM_{2.5}$ was officially incorporated into China's *Ambient Air Quality Standards*. In the third stage (2013–2019), $PM_{2.5}$ concentration rose steeply again in 2013 with an annual mean of 49.19 μg/m^3. The average number of hazy days in China reached 30 days. To improve air quality, China released the *Air Pollution Prevention and Control Action Plan* in September 2013. The new *Environmental Protection Law* was also enacted in 2014. China began to implement the most stringent air pollution control measures ever. China's air quality has gradually improved since 2015 under the environmental policies, showing a significant downward trend in the annual mean concentration of $PM_{2.5}$, which dropped to 36.23 μg/m^3 in 2019 with an average annual decrease of 2.16 μg/m^3.

According to the annual mean $PM_{2.5}$ concentration limits in China's *Ambient Air Quality Standards* (GB3095–2012), the annual mean of $PM_{2.5}$ concentration in 343 cities was divided into five intervals. The change of city number proportion in each concentration interval during the study period was analyzed (Fig. 4). The results show that: 1) The percentage of cities with annual mean $PM_{2.5}$ concentration below 15 μg/m^3 (WHO interim Target-3 level) was very small; even in 2019, only 4.66% of cities met this target. 2) The annual mean $PM_{2.5}$ concentration was lower than 35 μg/m^3 (China's concentration limit) in only 24.2% of all cities in 2013. This percentage reached 53.35% of the total by 2019. Since the implementation of "Air Plan A" in 2013, the number of cities

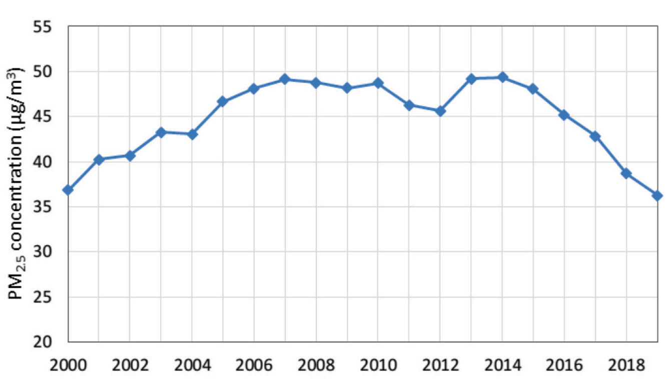

Fig. 3. The trend of annual mean $PM_{2.5}$ concentration in Chinese cities from 2000 to 2019.

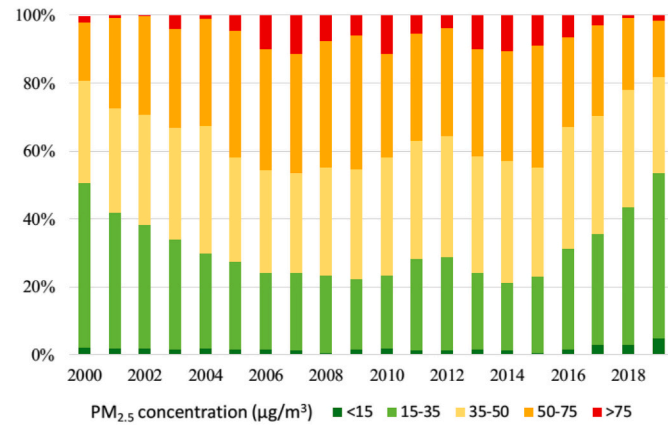

Fig. 4. The change in city number proportion in five concentration intervals from 2000 to 2019.

meeting the standard increased by 29.15%. 3) The largest percentage of cities with annual mean $PM_{2.5}$ concentration was in the range of 35–75 μg/m^3 (mild to moderate pollution), accounting for 44.91%–71.72%. 4) In 2006, 2007, 2010, 2013, and 2014, more than 10% of cities in China had an annual $PM_{2.5}$ concentration greater than 75 μg/m^3, categorizing them as severely polluted.

3.2. Spatio-temporal dynamic evolution of $PM_{2.5}$ concentration

3.2.1. Spatio-temporal evolution characteristics of $PM_{2.5}$ based on a space-time cube

According to the above analysis, the year 2013 represented a landmark for China's atmospheric environmental policy and was also an important turning point for a significant decline in $PM_{2.5}$. Therefore, the spatio-temporal evolution pattern of $PM_{2.5}$ is visualized in two periods based on space-time cubes (Fig. 5a, b). Video S1 details the dynamic 3D evolution of $PM_{2.5}$ concentration for the entire period from 2000 to 2019. Fig. 5a shows that the regions with high $PM_{2.5}$ concentration from 2000 to 2012 are mainly concentrated in the Jing-Jin-Ji Region, Fenwei Plain, Sichuan Basin, Central Yangtze Region, Yangtze River Delta, and southern Xinjiang. The high concentration area in Xinjiang is mainly affected by the Taklamakan Desert. Apart from Xinjiang, all other regions are highly populated and are dominated by heavy industries with high energy consumption and high pollution. Moreover, coal is commonly burned for heating in winter. From 2000 to 2010, the high $PM_{2.5}$ concentration areas expanded, peaking around 2010. Then, heavily polluted areas decreased in 2011 and 2012. From 2013 to 2019, the $PM_{2.5}$ concentration of most regions in China was on a gradual downward trend, and the areas with high values greatly decreased (Fig. 5b). Air quality improvements were most marked in densely populated urban agglomerations.

3.2.2. Spatio-temporal hot and cold spots patterns of $PM_{2.5}$ concentrations

Based on the space-time cube of $PM_{2.5}$ concentrations in China, we identified the hot and cold spots of $PM_{2.5}$ distribution and explored their dynamic aggregation characteristics from 2000 to 2019. The results demonstrate that 891 spatial locations are showing a spatio-temporal trend of cold or hot spots, accounting for 72.9% of the total 1222 locations nationwide. We identified 17 patterns of cold and hot spots (Table 2 and Fig. 6). However, the area distribution and the number of each pattern varied widely. There were a total of 616 spatio-temporal cold spots and 275 spatio-temporal hot spots. The number and distribution of hot/cold spots indicate that the air quality in most regions of China has been improving.

The hot spots were relatively concentrated in Eastern China, the Middle and lower Yangtze River, the Sichuan Basin, and southern Xinjiang. The categories included intensifying, persistent, sporadic, and

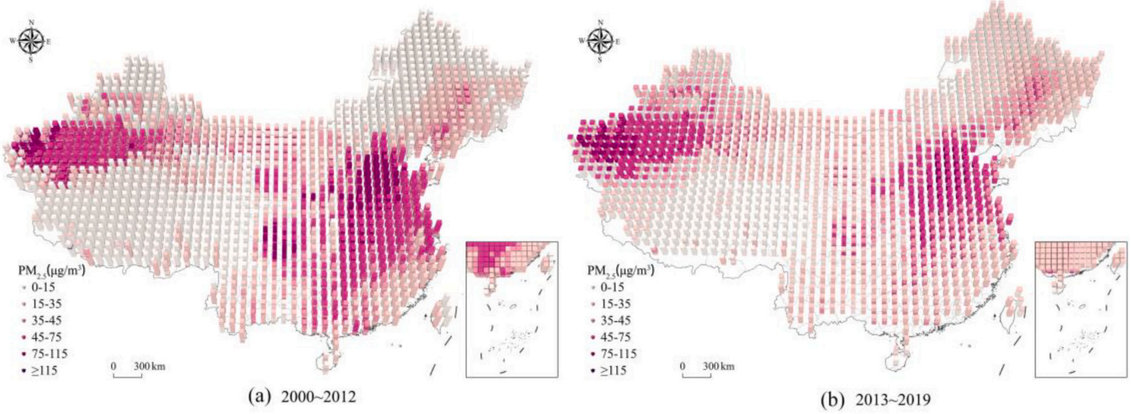

Fig. 5. Space-time cube of $PM_{2.5}$ concentrations in China. (a) 2000–2012; (b) 2013–2019.

Table 2
The number and spatial distribution of $PM_{2.5}$ spatio-temporal hot/cold spots.

Patterns	Number of hot spots	Distribution of hot spots	Number of cold spots	Distribution of cold spots
New	10	South-central Xinjiang	110	East part of the Yunnan-Kweichow Plateau, the west coast of the Taiwan Straits, The Hexi Corridor
Consecutive	6	Fenwei Plain, Southern Xinjiang	10	Eastern Tibetan Plateau
Intensifying	93	North China Plain, Southern Xinjiang	103	Central Tibetan Plateau
Persistent	59	Southern Fenwei Plain, Middle and Lower Yangtze River	237	Northern Xinjiang, Southwestern Tibetan Plateau, Greater Higgnan Mountains
Diminishing	1	Sichuan Basin	7	Northeastern part of Northeastern China, Northeastern Xinjiang
Sporadic	56	South-central Xinjiang, Fenwei Plain	139	North-central Tibetan Plateau, Parts of the Northeast Region, West of the Yunnan-Kweichow Plateau
Oscillating	2	Southeastern Xinjiang	4	Eastern Tibetan Plateau
Historical	48	Sichuan Basin, Parts of the Central Yangtze	6	Southern Xinjiang

historical hot spot patterns (Table 2). The number of persistent hot spot locations was the largest and were mainly distributed in the North China Plain and southern Xinjiang, indicating that the clustering of high $PM_{2.5}$ concentration in these regions increased. Persistent hot spot regions were mainly distributed in the southern Fenwei Plain and the Middle and lower Yangtze River, indicating that these regions have been the areas with high $PM_{2.5}$ concentrations for most of the last 20 years. Historical hot spot regions were mainly located in the Sichuan Basin and Central Yangtze, indicating that these regions were high $PM_{2.5}$ concentration areas previously, but not in recent years.

The cold spot regions were mainly located in the Tibetan Plateau, Greater Higgnan Mountains, Yunnan, the west coast of the Taiwan Straits, and northern Xinjiang. The types mainly included persistent, sporadic, new, and intensifying patterns (Table 2). The number of persistent cold spots was the largest and were mainly distributed in northern Xinjiang, southwestern Tibetan Plateau, and around the Greater Higgnan Mountains, indicating that $PM_{2.5}$ concentrations in these regions have been stable at lower levels in the past 20 years. There were also some new cold spots in the eastern part of the Yunnan-Kweichow Plateau, the west coast of the Taiwan Straits, and the Hexi Corridor, indicating that in these areas low-value clustering has become significant in recent years.

Finally, we visualized the results of the emerging spatio-temporal hot/cold spots in a 3D form for two periods (Fig. 6b-c). The full-period dynamic evolution video can be seen in Video S2. Our results show that the range of hot spot areas for $PM_{2.5}$ has been significantly reduced after 2013. Some regions such as the Sichuan Basin, Central Yangtze, and the Lanzhou-Xining urban agglomeration have been gradually withdrawn from hot spot areas. In recent years, new cold spot regions have appeared successively in the Yunnan-Guizhou region, Southeast China, and Northeast China. However, the Jing-Jin-Ji region and Fenwei Plain have remained hot spot areas for pollution until 2019.

3.3. Health impacts of air quality policies

3.3.1. Summary of the major air pollution control policies in China

The Chinese government declared war on air pollution in 2012, issuing a series of policies, regulations, and action plans (Table 3). The major governance measures included comprehensive controls of heavy pollution enterprises, adjustment of industrial and energy structure, technological innovation in pollution control, total coal control, and establishment of regional cooperation mechanisms. While draconian special action plans were implemented to significantly reduce extreme pollution incidents, China has also been piloting more alternative governance approaches, including more flexible market-based and bottom-up policies (Wang, 2021). In terms of the reduction in the concentration of various pollutants, the vast majority of action targets have been achieved (Zhang et al., 2019). In this paper, we analyzed the specific effects of these environmental policies by comparing different dimensions in time and space.

3.3.2. Spatio-temporal characteristics of $PM_{2.5}$ exposure following environmental policies enactment

We calculated the population and area exposure ratio in China for different $PM_{2.5}$ concentrations using the 1-km raster data of $PM_{2.5}$ and population density (Fig. 7). Our results indicate that the proportion of population exposure to $PM_{2.5}$ with a concentration above 35 $\mu g/m^3$ was above 70% until 2013. In 2009, the proportion of population exposure with moderate to high concentration reached 94.41% (nearly 1.25 billion people), indicating that most Chinese were chronically exposed to higher levels of $PM_{2.5}$ pollution. There was a significant decrease in

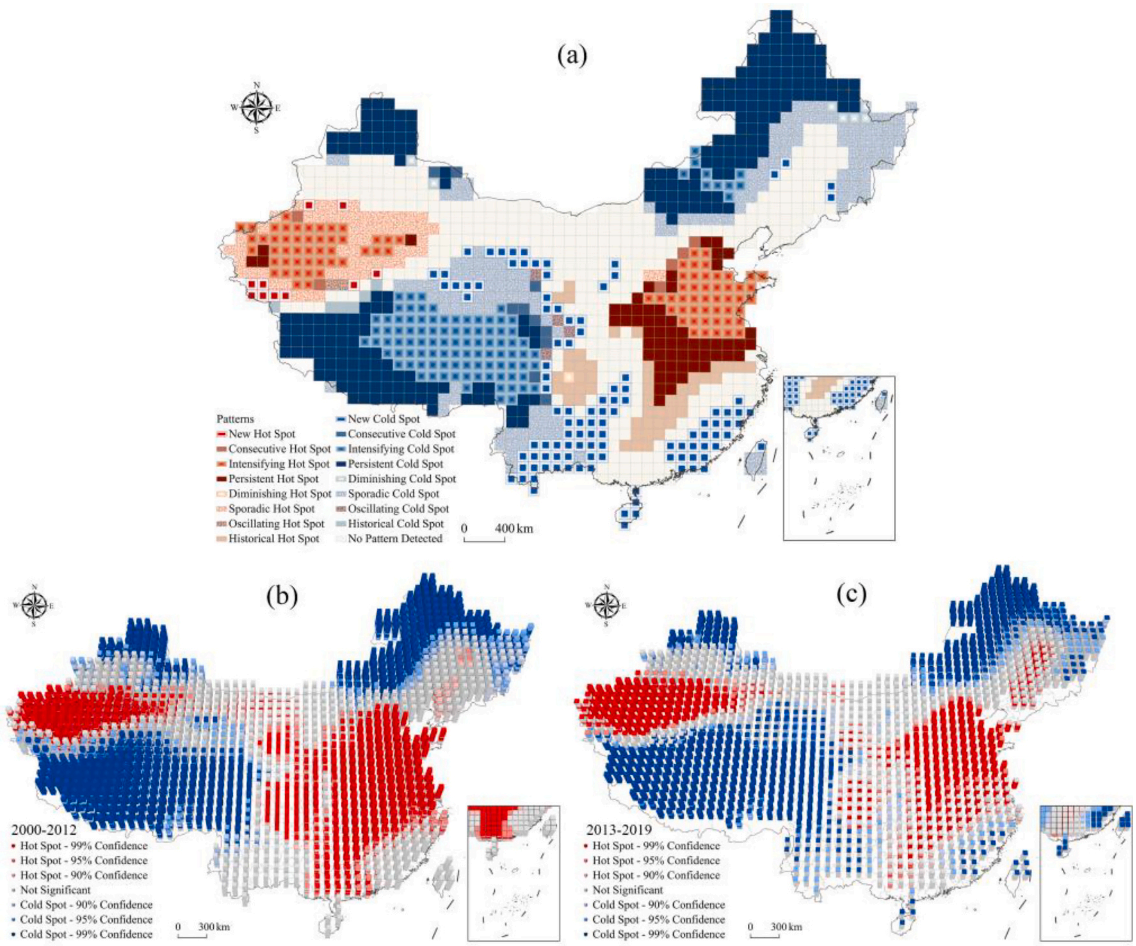

Fig. 6. The spatio-temporal cold/hot spots of $PM_{2.5}$ concentrations in China. (a) Spatio-temporal hot/cold spots patterns; (b) 3D map of spatio-temporal hot/cold spots, 2000–2012; (c) 3D map of spatio-temporal hot/cold spots, 2013–2019.

the proportion of population exposure to polluted air after 2013, from 77.41% in 2013 to 49.43% in 2019. Before 2013, the polluted areas with $PM_{2.5}$ concentrations above 35 μg/m^3 remained around 30%. The enactment of policies resulted in a steady decrease in polluted areas since 2013. Polluted areas decreased from 34.61% in 2013 to 21.11% in 2019 (total decrease of 13.50%).

Fig. 8a and Fig. 8b illustrate the spatial distribution of the change in $PM_{2.5}$ concentrations in China during the periods 2000–2012 and 2013–2019 (data have a 1-km resolution; a rise or fall of 10 μg/m^3 is deemed a significant change). Fig. 8c and Fig. 8d reflect the spatial distribution of China's population and economy to serve as a comparison to the $PM_{2.5}$ exposure analysis. From 2000 to 2012, the area with an increase in $PM_{2.5}$ concentration accounted for 54.2%, of which 18.3% was significant; the area where $PM_{2.5}$ concentrations decreased accounted for 45.8% of the total, of which 13.4% were significant. $PM_{2.5}$ concentrations rose significantly in the North China Plain, southern Xinjiang, Central Yangtze urban agglomeration, and Beibu Gulf. However, they significantly decreased in northern Sichuan, Ningxia, and Gansu. From 2013 to 2019, the area with increased $PM_{2.5}$ concentrations accounted for 34% of the total; the area with decreased concentration accounted for 65.8% of the total, of which 26.7% of the area had a significantly decreased concentration. Hu's line, proposed by Hu Huanyong in 1935, divides China into two regions (southeast and northwest) of comparable areas but drastically different in population size (Wang et al., 2019). Air quality has improved to some extent in almost all areas southeast of Hu's Line (Fig. 8b). The decrease was most significant in urban agglomerations, including Jing-Jin-Ji, Chengdu-Chongqing, Central Yangtze, Central Plain, Shandong Peninsula, and Pearl River Delta urban agglomeration. It is thus clear that while urban agglomerations are areas of severe air pollution, they are also the areas that had the best control effects in recent years. $PM_{2.5}$ concentrations increased on the Tibetan Plateau and Inner Mongolian Plateau, which are located northwest of Hu's Line.

3.3.3. *Premature deaths avoided by air quality policies*

Assessing the impacts of projects and policies aimed at air pollution reduction requires a quantitative analysis of the relationship between exposure and public health. Firstly, the IER model was used to assess the number of premature deaths from ambient $PM_{2.5}$ exposure. Then, based on the no policy scenario and the real scenario, we estimated the reduction in the number of premature deaths following the implementation of policies in 343 cities. The results show that in 2019 there were 1,023,000 $PM_{2.5}$-related premature deaths in China. In the absence of various air pollution control policies, the number would have been 1,200,000. Thus, air quality policies resulted in 177,000 (14.75%) fewer deaths. Most cities benefitted from this reduction, with only a few cities in the northwest and northeast recording no reduction in premature deaths (Fig. 9). The number of deaths decreased more in Eastern China, the Yangtze River Delta, and the Sichuan Basin, where the population density is high and pollution control policies are more stringent. Seven cities – Beijing, Tianjin, Shanghai, Chongqing, Chengdu, Guangzhou, and Shenzhen – saw the number of premature deaths fall by more than 2000. Cities with 1000–2000 reduced premature deaths are all located east of Hu's Line, except Lanzhou.

Table 3
Summary of the major air pollution control policies in China since 2012.

Time	Policies, regulations, and action plans	Main content
2012	Ambient Air Quality Standards (GB3095—2012)	Adds concentration limits for $PM_{2.5}$ and ozone; the annual mean and 24-h mean concentration limits of $PM_{2.5}$ is set at 35 μg/m^3 and 75 μg/m^3.
2013–2017	Air Pollution Prevention and Control Action Plan	Comprehensive control of air pollution by industrial enterprises; adjustment of industrial and energy structure; technological innovation in pollution control; establishment of regional cooperation mechanism.
2014	Work Plan to Enhance Air Pollution Control in the Energy Industry	Emphasizes pollution control in thermal power plants, petrochemical plants, and coal-fired boilers; total energy consumption control; supply of clean energy; efficient and clean conversion of coal.
2016	Atmospheric Pollution Prevention and Control Law of China (Revision)	Clarifies the responsibilities and obligations of the government, regulators, polluters, and the public for air pollution prevention and control; establishes a target responsibility system of local government and its evaluation system
2018–2020	Three-year Action Plan for Cleaner Air	Controls the production capacity of industries with high pollution and energy consumption; total coal consumption in key areas will continue to be controlled; development of green transportation system; adjust the structure of land use; control of non-point source pollution.
2017–2020	Comprehensive action to control air pollution in autumn and winter	Selects the most polluted areas in China, including the Jing-Jin-Ji region, the Yangtze River Delta, and the Fenwei Plain; Comprehensively controls scattered coal pollution; Strengthens oversight, assistance, and quantify accountability.

4. Discussion

4.1. Application prospects of the emerging spatio-temporal hot spots analysis of environmental pollutants

The analysis of spatial and temporal characteristics of environmental pollutants is of great significance to pollution prevention and control and policymaking. Compared with conventional spatio-temporal analyses, the dynamic 3-D analysis based on space-time cubes provides improved visualization effects. The emerging spatio-temporal hot spots analysis is more refined than a traditional spatial hot spots analysis and can identify 17 patterns to better support the government's grid modernization governance. This method has been applied in various fields, such as infectious diseases, natural disasters, and human mobility (Allen et al., 2021; Kang et al., 2018; Mo et al., 2020). However, applications in the field of environmental pollution are still poorly developed (Fang and Lu, 2011). We applied this method to conduct an exploratory analysis and expect environmental scholars to pay more attention to this methodology in the future.

4.2. Comparison and analysis of health assessment results with predecessors' research

There have been already many assessments of the number of premature deaths caused by air pollution in China. The results of this study are consistent with previous studies. Yin et al. (2020b) estimated that 851,660 deaths in China were attributable to ambient $PM_{2.5}$ pollution in 2017. Xue et al. (2019) estimated that the premature deaths attributable to long-term $PM_{2.5}$ exposure were 1.0 million in 2017. Compared with 2013, Wang et al. (2021a) estimated that in 74 cities the number of premature deaths attributable to long-term $PM_{2.5}$ exposure decreased by almost 53,100 in 2018. Yue, He et al. (2020) estimated that the annual deaths attributable to $PM_{2.5}$ pollution in 2017 decreased by 64,000 compared to 2013. Lu et al. (2019) estimated that the premature mortality associated with $PM_{2.5}$ concentrations dropped from 1,078,800 in 2014 to 962,900 in 2017. Our results show that $PM_{2.5}$-related premature deaths in China were 1,023,000 in 2019. As a result of air quality policies, there were 177,000 fewer deaths. This result is higher than what was reported in previous studies. This could be explained by the fact that we evaluated policies effects from 2013 to 2019. Also, unlike previous studies, our method was based on a no-policy scenario.

4.3. Research uncertainties and prospects

Our assessments of health benefits were subject to some

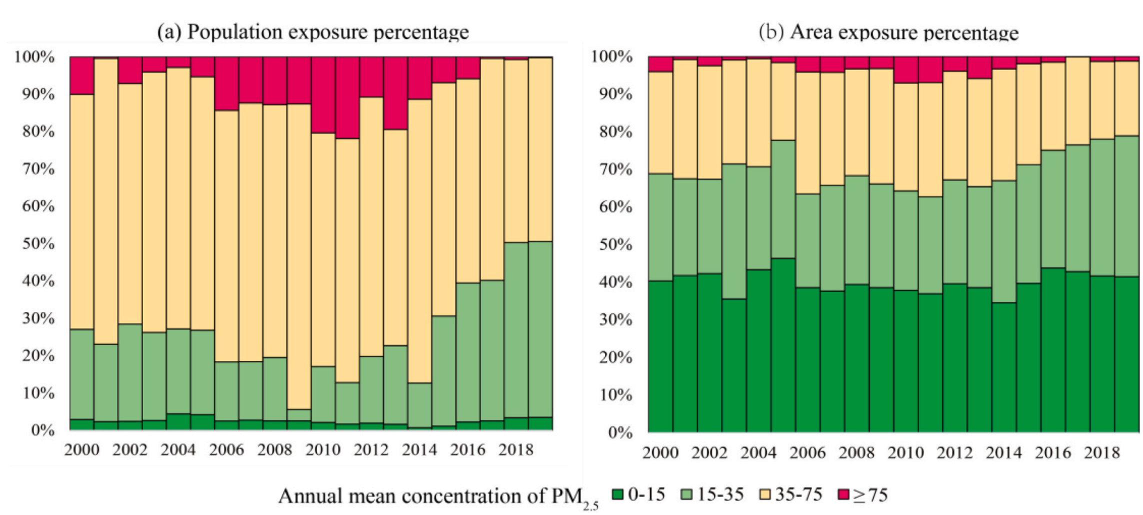

Fig. 7. Percentage of population (a) and area (b) exposure to different concentrations of $PM_{2.5}$ from 2000 to 2019 in China.

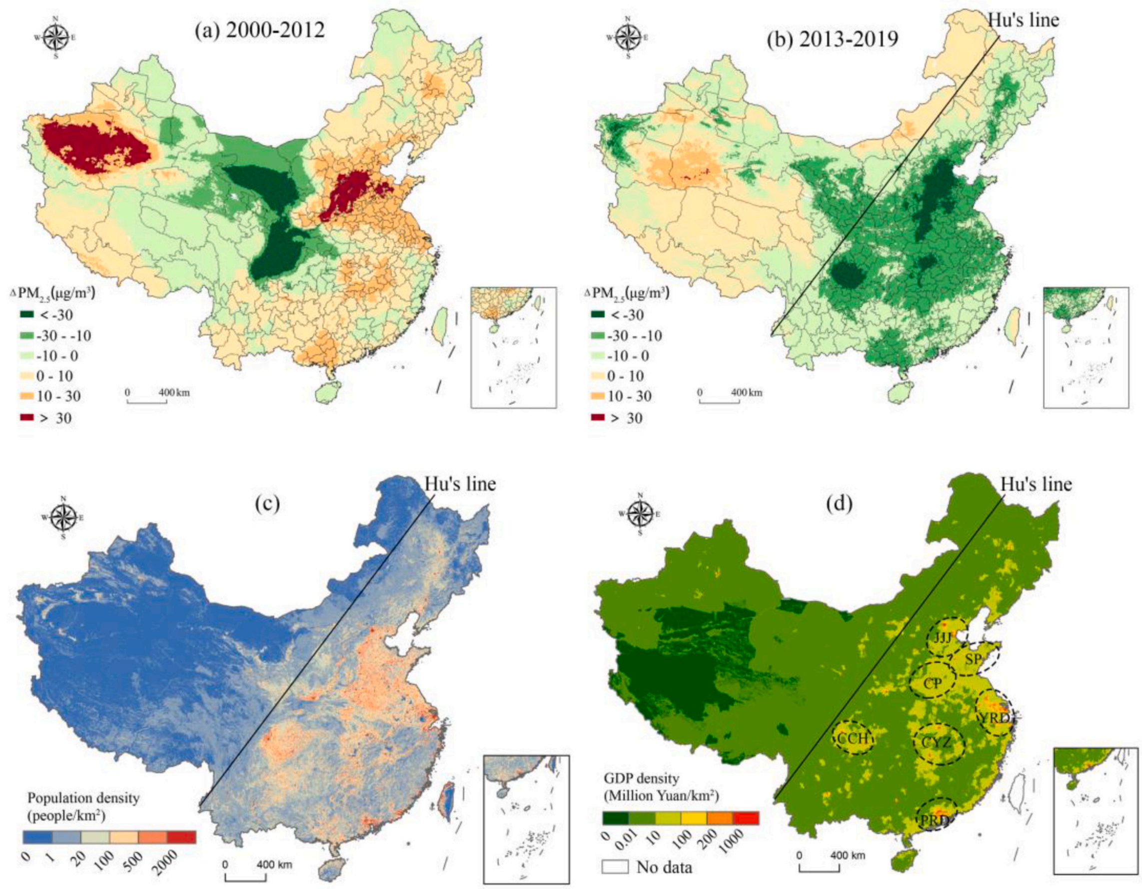

Fig. 8. Changes in $PM_{2.5}$ concentrations in China from 2000 to 2019. (a) Changes in 2000–2012; (b) Changes in 2012–2020; (c) population density in 2019 as a reference; (d) GDP density in 2015 as a reference. Abbreviation of urban agglomerations: Jing-Jin-Ji (JJJ), Yangtze River Delta (YRD), Pearl River Delta (PRD), Central Yangtze (CYZ), Chengdu-Chongqing (CCH), Shandong Peninsula (SP), Central Plain (CP).

uncertainties. Total $PM_{2.5}$-related deaths differed depending on the method used (Maji et al., 2018b). In calculating the health effects of policies enactment, we predicted a hypothetical scenario without policies. This linear prediction, which had a fitting coefficient (R^2) of 0.7434, was based only on historical data and did not consider future nonlinear changes in the economy, meteorology, and other factors. For example, meteorology played a positive role in improving air quality in the context of China's clean air policy during the period 2016–2019 (Kou et al., 2021). This may have caused the health effects of this research to be overestimated. In addition, with progress in medical technology, the population ageing in China is accelerating in recent years (Zhu et al., 2019). In this aspect, the number of premature deaths calculated in this research may be underestimated. Although the health effects of environmental policies calculated by various scholars are different, all conclusions show that the effect is positive and significant. China's air pollution is increasingly decoupled from economic development (Zhang et al., 2020). We hope that China's experience can be applied to other heavily polluted regions, such as in India (Fuller and Font, 2019).

Small particle pollution has health impacts even at very low concentrations, and the WHO guideline of $PM_{2.5}$ is 5 μg/m^3 annual mean (WHO, 2021). The "beautiful China" targets require all cities to lower the annual concentration of $PM_{2.5}$ to less than 35 μg·m^3 (WHO Interim Target-1 level) by 2035. Considering the rapid development of China's economy and urbanization, the country has a long way to go to achieve air pollution control. With the decline in $PM_{2.5}$, ozone pollution has gradually become the main pollutant in many cities in China (Li et al., 2019). Moreover, China has pledged to become carbon neutral by 2060, which is expected to contribute to more than 80% reductions in $PM_{2.5}$ and O_3 concentrations relative to the 2020 levels (Shi et al., 2021). Thus, we should focus more on the collaborative governance of $PM_{2.5}$, O_3, and CO_2 emissions in the future. Besides, we should value the telecoupling of environmental policies and air pollution (Liu et al., 2020), considering the spatial spillover effects of air pollutants (Peng et al., 2021) and transboundary spillovers of environmental regulations (Feng et al., 2020; Jiang and Bai, 2018).

5. Conclusions

Compared to previous studies, the contribution of this paper is principally reflected in the following two aspects: 1) We analyzed spatio-temporal dynamic 3D characteristics of $PM_{2.5}$ concentrations at a fine scale using emerging spatial and temporal hot spots; 2) The reduction of premature deaths affected by environmental policies on the city scale was estimated using improved health effect assessment methods. This study shows that China's air pollution control policies from 2013 to 2019 have achieved remarkable success. Many policies and actions could be used by some developing countries for reference, such as India and Vietnam with more and more serious air pollution. In addition, the scenario comparison method constructed in this paper is more accurate than the traditional path, which can provide implication for further studies. The main findings are:

(1) The overall evolution trend of the average $PM_{2.5}$ concentration in China from 2000 to 2019 followed an "M" shape. The year 2013 was a landmark time for China's atmospheric environmental policy and was also an important turning point for the significant decline in $PM_{2.5}$. The annual mean $PM_{2.5}$ concentration was

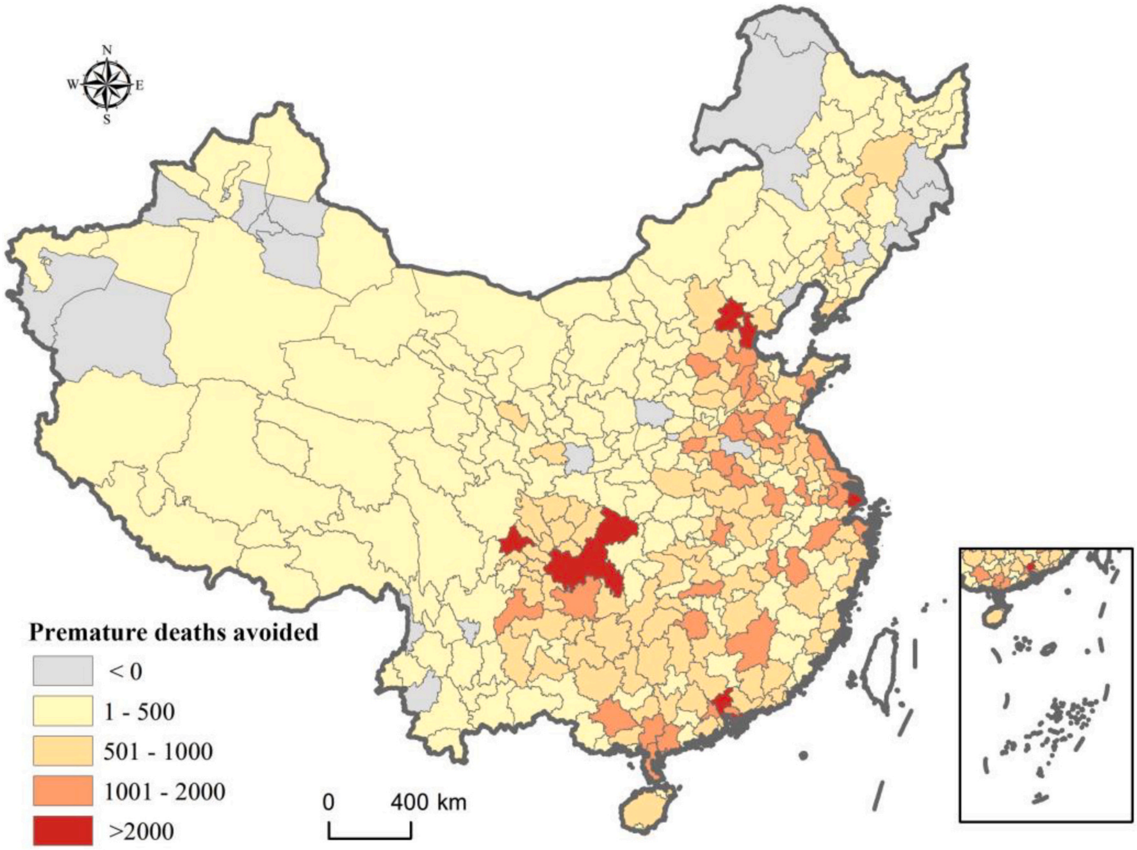

Fig. 9. Premature deaths avoided in 2019 by the enactment of air quality policies (data are for cities).

lower than 35 μg/m^3 (China's concentration limit) accounting for only 24.2% of all cities in 2013. This percentage reached 53.35% of the total by 2019.

(2) From 2013 to 2019, the $PM_{2.5}$ concentrations of most regions in China showed a gradual downward trend, and the areas with high pollution levels were greatly reduced. There was a significant decrease in the proportion of population exposure to polluted air after 2013, from 77.41% in 2013 to 49.43% in 2019. The polluted area exposure to $PM_{2.5}$ (>35 μg/m^3) decreased from 34.61% in 2013 to 21.11% in 2019. From 2013 to 2019, the area with decreased concentrations accounted for 65.8% of the total, mainly distributed east of Hu's Line. Urban agglomerations are serious areas of air pollution, but also the areas that had the best control effects in recent years.

(3) There were a total of 616 spatio-temporal cold spots and 275 spatio-temporal hot spots in China from 2000 to 2019, indicating that the air quality in most regions of China is improving. The hot spot regions are concentrated in Eastern China, the Middle and lower Yangtze River, and the Sichuan Basin. The hot spot categories include intensifying, persistent, sporadic, and historical hot spot patterns.

(4) The health benefits of China's environmental policies since 2013 have been significant. $PM_{2.5}$-related premature deaths in China were 1,023,000 in 2019. However, without the release of various air pollution control policies, the number would have been 1,200,000. As a result of environmental policies, by 2019 there were 177,000 (14.75%) fewer deaths in China.

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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.

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