Effects of Anthropogenic Emissions from Different Sectors on PM$_{2.5}$ Concentrations in Chinese Cities

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1. Introduction

Particulate matter (including PM$_{2.5}$ and PM$_{10}$, etc.), particularly fine particulate matter (PM$_{2.5}$), is an air pollutant that exerts an important negative impact on public health [1–4]. Worldwide, more than 3.2 million people die prematurely due to outdoor particulate matter exposure each year [5]. In recent years, with the acceleration of China’s industrialization and urbanization and the continuous expansion of the urban scale, PM$_{2.5}$ pollution has gradually attracted the attention of the government and academic circles [6–8].
Clarifying the mechanism of PM$_{2.5}$ pollution is key to formulating effective pollution control policies. Natural geographic elements, including climate and topography, exert an important impact on PM$_{2.5}$ [9–16]. Related studies have discussed meteorological factors, including temperature [17–19], humidity [20,21], wind speed [22,23], precipitation [24], atmospheric pressure [25], boundary layer height [26,27], solar radiation [28], and other factors that contribute to PM$_{2.5}$. In addition to physical and geographic elements, human factors also exert a significant impact on PM$_{2.5}$ concentrations [29]. Researchers have discussed the impact of many aspects on PM$_{2.5}$ concentrations, such as land use [30,31], urbanization [32,33], transportation [34], economic development [35,36], and emissions premises [37–41]. Studies including [42] and others have studied the impact of reforestation and conversion of arable land on future air quality in the southern United States. The results showed that reforestation in the southeastern part of the United States led to a slight increase in summer PM$_{2.5}$ in the southeastern United States, and the conversion of forest land to cultivated land led to an increase in annual PM$_{2.5}$ concentrations. Studies including [43] and others have studied the impact of urban expansion on air quality in eastern China. The results have shown that intensive urbanization has an appropriate dilution effect on the concentrations of surface pollutants, but improper local emission control measures will aggravate regional haze pollution. Studies including [44] and others found that improper local emission control has also been found to have a great impact on light pollution among regional haze pollution. Studies including [45] and others have discussed the relationship between urbanization and other human factors, including clean energy consumption, emission reduction input, industry, and PM$_{2.5}$ concentrations. The results have shown that the increase in PM$_{2.5}$ concentrations is associated with urban areas. The protection of chemical and industrial growth is consistent, and increasing emissions reduction inputs and clean energy can slow the trend of increasing PM$_{2.5}$ concentrations. Studies including [46] and others discussed the impact of social and economic development on major Chinese cities in terms of population density, economic growth, industrial base, industrial dust emissions, road density, trade openness, and energy consumption. The results showed that population density, industrial base, industrial dust emission, and road density have a significant positive effect on PM$_{2.5}$ concentrations, while economic growth has a negative effect on PM$_{2.5}$ concentrations. Studies including [35] and other studies have found that industrialization, urbanization, and economic growth in China have a positive correlation with PM$_{2.5}$ concentrations. Studies including [47] and others found that land use/cover changes in PM$_{2.5}$ concentrations showed a significant difference in different regions. Studies including [48] and others discussed the relationship between urban spatial structure and air quality in the United States, and found that proximate forests to urban areas reduce the number of AQI exceedance days. In addition, related researchers have integrated natural and human factors to discuss their influence on air quality [49,50]. Studies including [51] and others explored the impact of future climate change and anthropogenic emissions on the air quality in Portugal and Porto metropolitan areas in 2050 through different scenarios. The results showed that climate change and anthropogenic emissions have obvious temporal and spatial differences in the impact of air quality.

In summary, although existing research has made considerable progress in understanding the influence mechanism of PM$_{2.5}$ concentrations, there remain some shortcomings. Existing studies mostly analyze the driving mechanism at a single temporal and spatial scale, and the differences of impact factors at different temporal and spatial scales are insufficiently considered. As far as anthropogenic emission factors are concerned, the impact mechanism of different sectors and different types of anthropogenic emissions on PM$_{2.5}$ at different temporal and spatial scales is still unclear. This study focused on the entirety of China and analyzed the impact mechanism of emissions from different sectors on PM$_{2.5}$ changes at different temporal and spatial scales. In addition, unlike most previous studies, which have only roughly characterized the humanistic driving mechanism through statistical data, this study focused more on the differences within the emission sector and
explored the impact of anthropogenic emissions between different sectors on PM$_{2.5}$ to clarify the difference in the impact of sector emissions on PM$_{2.5}$ from a more detailed perspective.

Based on the emission inventory and site monitoring data, this study used the geographic detector method to explore the influence mechanism of the anthropogenic emission factors of different sectors on the PM$_{2.5}$ concentrations. The research results will help researchers improve the accuracy of air quality forecasting models and also provide a basis and reference for government departments to formulate more accurate particulate matter emission government control policy.

2. Materials and Methods

2.1. Study Area

This study takes China as the research area and selects 366 major cities as samples to analyze the impact of the emissions of different sectors on the PM$_{2.5}$ concentrations of major cities. Considering China’s natural and economic and social conditions and referring to the research of [52], the China region is divided into ten zones (Figure S1): the upper zone of the Yellow River (UYR); the middle and upper zone of the Pearl River (MUPR); the middle zone of the Yellow River (MYR); the northern coastal zone (NC); the northeast zone (NE); the middle and upper zone of the Yangtze River (MUYR); the southeast coastal zone (SC); the Xinjiang zone (XJ); the Qinghai-Tibetan Plateau (QTP); and the eastern coastal area (EC). Furthermore, part of the district is divided into two regions, the south and the north. NE, MYR, UYR, and NC belong to the northern region, while SC, MUPR, EC, and MUYR belong to the southern region.

2.2. Data

The data used in this study include daily PM$_{2.5}$ monitoring data from 366 cities (Figure S2) from 2015 to 2017 (National Environmental Monitoring Center). Based on this data, we can obtain the annual average concentrations (Figure 1a) from 2015 to 2017, as well as the seasonal average concentrations (Figures S2 and S3). The anthropogenic emission data of primary PM$_{2.5}$, nitrogen oxides (NO$_X$), volatile organic compounds (VOC$_S$), sulfur dioxide (SO$_2$) and ammonia (NH$_3$) come from the 2016 Tsinghua University Emission Inventory (MEIC) (http://www.meicmodel.org/ (accessed on 10 December 2018)) (Figure 1b–f), the grid resolution is 0.25° × 0.25°, and the temporal resolution is month by month. The emission sector is divided into five sectors: industrial sources, agricultural sources, transportation sources, power sources and residential sources. The types of pollutants in each sector are as follows (Figures S4–S8): primary industry PM$_{2.5}$, primary power PM$_{2.5}$, primary residential PM$_{2.5}$, primary transportation PM$_{2.5}$, industrial NO$_X$, power NO$_X$, residential NO$_X$, transportation NO$_X$, industry VOC$_S$, power VOC$_S$, residential VOC$_S$, transportation VOC$_S$, agricultural NH$_3$, industrial NH$_3$, residential NH$_3$, transportation NH$_3$, industrial SO$_2$, and power SO$_2$.

2.3. GeoDetector Model

Geographic detectors are a set of statistical methods that use spatial similarity to detect the influence of independent variables on dependent variables and reveal the driving force behind the phenomenon. This method has no linear assumptions and has clear physical meaning. It includes 4 modules: the factor detection module, interaction function detection module, risk area detection module, and ecological detection module [53]. This study uses the factor detection module in GeoDetector to evaluate the contribution of pollutants emitted by different sectors to the PM$_{2.5}$ concentrations of major cities in China. The factor detection module can express the degree of interpretation of the independent variable to the dependent variable through the $q$ value. For specific methods, please refer to related research [54,55].
Figure 1. Maps of (a) annual average concentrations of PM$_{2.5}$ (2015–2017) and (b) primary PM$_{2.5}$ emissions, (c) NO$_X$ emissions, (d) SO$_2$ emissions, (e) NH$_3$ emissions, and (f) VOC$_S$ emissions from Chinese cities in 2016 with a resolution of 0.25 $\times$ 0.25.

The factor detection module used in this article is used to detect the spatial differentiation of the dependent variable and quantify the degree of interpretation of a certain independent variable to the dependent variable, measured by the $q$ value. Assume that the PM$_{2.5}$ concentrations in the area in which the city is located are composed of daily emission data of 366 cities across the country. Assuming that there may be a factor that affects the concentrations of PM$_{2.5}$, expressed as $A = \{A_h\}$, $h = 1, 2, \ldots, L$, $L$ is the number of influencing factors, $A_h$ is the different types of influencing Factors A, and A-type $h$ corresponds to one or more regional subsets of the city in space. To detect the spatial correlation between influencing Factor A and urban PM$_{2.5}$ concentrations, the layers of influencing Factor A and the urban PM$_{2.5}$ concentrations map are superimposed. In the $h$ type of influencing Factor A, the discrete variance of urban PM$_{2.5}$ concentrations is denoted as $\sigma^2_h$, and the degree of interpretation of PM$_{2.5}$ concentrations by influencing Factor A can be expressed as:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma^2_h}{N \sigma^2}$$

(1)
In the formula, \( q \) is the explanatory power of urban PM\(_{2.5} \) concentrations influencing factors, and its value range is [0, 1]; \( L \) is the number of urban subregions divided by influencing factors, which this article uses equal interval classification to divide into 6 levels; \( h \) is a certain subarea; \( N_h \) is the number of samples in a given subarea; \( N \) is the number of samples in the entire study area; \( \sigma_h^2 \) is the discrete variance of the PM\(_{2.5} \) concentrations in a given subregional city; \( \sigma^2 \) is the variance of the PM\(_{2.5} \) concentrations in the entire regional city. If the \( q \) value of a certain influencing factor is higher, its explanatory power is stronger, and the influence of this factor on urban PM\(_{2.5} \) concentrations is stronger. Conversely, if the \( q \) value of a certain influencing factor is smaller, its explanatory power is weaker, and the influence of this factor on urban PM\(_{2.5} \) concentrations is weaker. In extreme cases, a \( q \) value of 0 indicates that the influencing factor and urban PM\(_{2.5} \) concentrations score have no relationship. A \( q \) value of 1 indicates that the influencing factors completely affect the distribution of urban PM\(_{2.5} \) concentrations.

3. Results

3.1. Analysis on the National Annual Scale

The driving factors of PM\(_{2.5} \) concentrations in all Chinese cities have significant annual changes on an annual scale. If the emission sectors are not considered, the primary two factors influencing the concentrations of PM\(_{2.5} \) on the national annual scale are NH and P_PM (Figure 2). If the emission sectors are considered, the dominant factors that affect PM\(_{2.5} \) concentrations on the national annual scale come from residential sources. Among them, the dominant factor is R_NO (\( q = 0.20 \)), followed by R_VO (\( q = 0.18 \)), R_NH (\( q = 0.16 \)) and R_SO (\( q = 0.14 \)) (Figure 2).

![Figure 2](image-url)

**Figure 2.** The \( q \) value of the driving factor on the national annual and seasonal scales. (P_I_PM denotes primary industry PM\(_{2.5} \); P_P_PM denotes primary power PM\(_{2.5} \); P_R_PM denotes primary residential PM\(_{2.5} \); P_T_PM denotes primary transportation PM\(_{2.5} \); I_NO denotes industrial NO\(_X\); P_NO denotes power NO\(_X\); R_NO denotes residential NO\(_X\); T_NO denotes transportation NO\(_X\); I_VO denotes industry VOC\(_S\); P_VO denotes power VOC\(_S\); R_VO denotes residential VOC\(_S\); T_VO denotes transportation VOC\(_S\); A_NH denotes agricultural NH\(_3\); I_NH denotes industrial NH\(_3\); R_NH denotes residential NH\(_3\); T_NH denotes transportation NH\(_3\); I_SO denotes industrial SO\(_2\); and P_SO denotes power SO\(_2\)).

3.2. Analysis on the National Seasonal Scale

If the emission sectors are not taken into account, the dominant factors that affect the PM\(_{2.5} \) concentrations on the national scale in spring are NO and NH (Figure 2). In summer, these types of anthropogenic emissions have similar effects on PM\(_{2.5} \) concentrations...
on the national scale. Similar to summer, these types of anthropogenic emissions have similar effects on PM$_{2.5}$ concentrations in autumn (except SO). However, the influence of NH and P_PM on PM$_{2.5}$ concentrations are stronger than other factors in winter on the national scale.

If the emission sectors are considered, traffic sources play a leading role in the influence of PM$_{2.5}$ concentrations compared with several other emission sources in spring on the national scale (Figure 2). The contribution of the influencing factors is ranked as follows: T_NO ($q = 0.13$), T_SO ($q = 0.12$), T_VO ($q = 0.12$). Similar to spring, the main driving factors come from traffic sources in summer. T_NO ($q = 0.17$) ranks first, followed by T_SO ($q = 0.16$) and T_NH ($q = 0.15$). In autumn, residential sources and traffic emissions play a leading role in PM$_{2.5}$ concentrations and have similar effects on the national scale. R_NO ($q = 0.18$) and R_NO ($q = 0.17$) are the top two factors. Similar to autumn, residential sources and traffic sources in winter play a leading role in the PM$_{2.5}$ concentrations and have similar effects, and the dominant factors are T_NO and T_SO.

3.3. Analysis on the Regional Annual Scale

If the emission sectors are not considered, these types of anthropogenic emissions have similar effects on PM$_{2.5}$ concentrations in most regions on the annual scale (except MYR and NC) (Figure S10). NH is the dominant factor of PM$_{2.5}$ concentrations in NC, while P_PM and NH3 are the two main factors on PM$_{2.5}$ concentrations in MYR.

If the emission sectors are taken into account, residential sources are the basic factors on PM$_{2.5}$ concentrations in most Chinese urban areas (except MUPR) (Figure 3). The northern area is dominated by R_VO and R_NH, while some southern areas (EC and MUYR) are dominated by R_NO. For the XJ and QTP regions, the dominant factors affecting PM$_{2.5}$ concentrations are R_SO and R_NO, respectively.

3.4. Analysis on the Regional Seasonal Scale

If the emission sectors are not considered, NH is the dominant factor in northern China and SC in spring, and NO is the dominant factor in southern EC and MUYR (Figure S10). In summer, NH is the dominant factor of PM$_{2.5}$ concentrations in most northern regions (except UYR) and in southern MUYR, VO is the dominant factor in URY and SC, and SO is the dominant factor in MUPR. In autumn, P_PM is the dominant factor of PM$_{2.5}$ concentrations in NE, MYR, and SC. NH is the dominant factor of PM$_{2.5}$ concentrations in NC and MUYR, and the dominant factor of PM$_{2.5}$ concentrations in MUPR and UYR is VO. In winter, however, NH is the dominant factor of PM$_{2.5}$ concentrations in NC, MYR, XJ, EC, SC and MUYR. VO is the dominant factor of PM$_{2.5}$ concentrations in MUPR and NE, and SO is the dominant factor of PM$_{2.5}$ concentrations in UYR in winter.

If the emission sectors are considered, emissions from residential sources and traffic sources are the dominant factors affecting the change in PM$_{2.5}$ concentrations in spring in most regions (Figure 3). NE, NC, MYR in the northern region and SC in the southern region are dominated by residential source emissions, while traffic emissions dominate in southern EC and MUYR. Similar to spring, summer residential and traffic sources remain the basic influencing factors for PM$_{2.5}$ concentrations changes in most parts of the country. Among them, NC, MYR, and XJ in the north and EC and MUYR in the south are mainly due to traffic emissions, whereas residential source emissions play a leading role in the southern MUPR and SC. In autumn, residential source emissions are the dominant factor in the changes in PM$_{2.5}$ concentrations in northern regions (UYR, NE, NC, MYR), with the R_VO factor being the primary influencing factor, followed by R_NH. In winter, traffic emissions are the dominant factor affecting the changes in PM$_{2.5}$ concentrations in the XJ, MYR, and EC regions, whereas residential source emissions are the dominant factors in the UYR, NC, and MUYR regions.
Figure 3. The $q$ value of the driving factor on the regional annual and seasonal scales. (P_I_PM denotes primary industry PM$_{2.5}$; P_P_PM denotes primary power PM$_{2.5}$; P_R_PM denotes primary residential PM$_{2.5}$; P_T_PM denotes primary transportation PM$_{2.5}$; I_NO denotes industrial NO$_x$; P_NO denotes power NO$_x$; R_NO denotes residential NO$_x$; T_NO denotes transportation NO$_x$; I_VO denotes industry VOC$_S$; P_VO denotes power VOC$_S$; R_VO denotes residential VOC$_S$; T_VO denotes transportation VOC$_S$; A_NH denotes agricultural NH$_3$; I_NH denotes industrial NH$_3$; R_NH denotes residential NH$_3$; T_NH denotes transportation NH$_3$; I_SO denotes industrial SO$_2$; and P_SO denotes power SO$_2$).

4. Discussion

The concentrations of PM$_{2.5}$ is affected by both natural and human factors, and anthropogenic emissions play an important role in its formation. Numerous studies have analyzed the formation of PM$_{2.5}$ and the influencing factors of its concentrations [56,57], but few studies have focused on the impacts of these factors on PM$_{2.5}$ concentrations from the perspective of sector emissions. In addition, the research results can provide a more accurate reference for formulating PM$_{2.5}$ control policies. In this paper, five types of pollutants emitted by five sectors, including residential sources, power, transportation, industry, and agriculture, were selected as driving factors. Based on the GeoDetector model, the impact of emission factors on the PM$_{2.5}$ concentrations at different temporal and spatial scales was analyzed. The study found obvious seasonal and regional changes in the impact of pollutant emissions from different sectors on PM$_{2.5}$ concentrations in Chinese cities. These variations are due mainly to the temporal and spatial differences in the emission of different precursors and photochemical reactions. Of course, anthropogenic emissions are also the main factors influencing the temporal and spatial differences in PM$_{2.5}$ concentrations in China and even at the global scale [58–60].

At the national scale, residential emissions are the main influencing factor of the PM$_{2.5}$ concentrations changes through the whole year. This result also verifies the proposal by other researchers that residential emissions play an important and non-negligible
role in air pollution control [61, 62]. However, at the national seasonal scale, the main driving factors of PM$_{2.5}$ concentrations show more significant changes. The impact of residential emissions on PM$_{2.5}$ concentrations in autumn and winter is stronger than that in spring and summer. These differences may be due to the unfavorable meteorological conditions of the planetary boundary layer in autumn and winter, such as temperature inversion and relatively frequent weak surface wind speed; moreover, the heating of living spaces and biomass burning in autumn and winter may easily cause an increase in PM$_{2.5}$ concentrations [10, 11, 63, 64]. It is worth noting that ammonia emissions exert a stronger impact on PM$_{2.5}$ in winter compared to the other three seasons regardless of whether sectoral emissions are considered. Since the emission of NH$_3$ in winter is lower than in other seasons, its impact is also higher than in other seasons, indicating that NH$_3$ plays a very important role in the production of PM$_{2.5}$ in winter, which is consistent with previous studies [65, 66]. Therefore, measures to limit NH$_3$ emissions should be considered when reducing PM$_{2.5}$ pollution in winter to achieve better pollution control effects.

At the regional scale, we found that the impact of residential emissions on PM$_{2.5}$ concentrations is dominant in the northern region and part of the southern region (MUYR and EC) through the whole year. Moreover, residential emissions also play a leading role in most seasons in the northern region. This impact may be because coal combustion and biomass combustion accounted for a large proportion of residential sources in the northern region, and these sources exert a greater impact on PM$_{2.5}$ concentrations, especially in spring, autumn and winter, which is consistent with existing studies [67–69]. In addition, the importance of residential source NH$_3$ emissions has been neglected. Studies have shown that residential NH$_3$ emissions exert a significant impact on PM$_{2.5}$ concentrations at the regional annual scale and in most seasons in northern China. This finding is consistent with related studies. For example, NH$_3$ emissions from urban residential sewage account for a relatively high proportion of total NH$_3$ emissions and have an important impact on PM$_{2.5}$ concentrations [39]. It is worth noting that traffic emissions play a leading role in the four seasons for MUYR and EC in southern China, MYR and NC in northern China, and on a national scale. China’s national statistics [70] show that from 1990 to 2012, the number of motor vehicles in China has increased 22 times in 22 years, and traffic emissions have become one of the largest sources of air pollution in China. On the other hand, this may be due to the fact that these areas are located in the central and eastern parts of China, with higher road network density, higher car ownership, and accelerated photochemical reactions under suitable weather conditions, which have an important impact on PM$_{2.5}$ concentrations [7, 71, 72].

The effects of primary emissions and secondary precursors on PM$_{2.5}$ concentrations have obvious differences at different temporal and spatial scales. At the annual scale, whether national or regional, primary PM$_{2.5}$ emissions contribute less to the PM$_{2.5}$ concentrations than secondary emissions. This finding is consistent with previous research, indicating that secondary emissions make an important contribution to PM$_{2.5}$ concentrations [73]. At the national seasonal scale, the contribution of primary PM$_{2.5}$ to the PM$_{2.5}$ concentrations is equivalent to that of secondary emissions, and the dominant factor comes from the primary emission of PM$_{2.5}$ from transport sources. However, on the regional seasonal scale, the contribution of primary PM$_{2.5}$ to PM$_{2.5}$ concentrations is significantly different from that of secondary precursor emissions. Therefore, when formulating PM$_{2.5}$ control policies, it is necessary to consider the actual conditions of the region and use differentiated emission control policies in different regions and seasons.

This study comprehensively quantifies the impact of different sectors’ emissions on PM$_{2.5}$ concentrations. The results of the study can help us understand the anthropogenic emission mechanism of PM$_{2.5}$ pollution changes and provide a reference for follow-up research and the formulation of policies and measures for related sectors. However, there are some limitations. (1) Due to the uncertainties in the emission inventory adopted, our research results will also have corresponding uncertainties. Moreover, given data availability limitations, the current inventory data used is only for one year (2016); data from other
years need to be analyzed in future work. (2) Given length restrictions and the previous research results that have been obtained, this article does not consider meteorological factors in its focus. In the future, it will be necessary to comprehensively consider the impact of land use/cover change, topography, and socioeconomic factors on PM$_{2.5}$ concentrations. (3) Related research shows that the concentrations of PM$_{2.5}$ and O$_3$ sometimes fluctuate, which also makes it difficult to formulate pollution control policies. Future research will combine the two pollutants of PM$_{2.5}$ and O$_3$ for analysis, thereby clarifying the impact mechanisms and formulating a more accurate policy reference for the government to comprehensively control air pollution.

5. Conclusions

The results of this study show that the effects of emission factors among various sectors on PM$_{2.5}$ concentrations present large regional and seasonal differences. Residential emissions were the dominant driver at the national annual scale, and also played the leading role at the regional annual scale and during most of the seasons in northern China. Residential NH$_3$ emissions exert a significant impact on PM$_{2.5}$ concentrations at the regional annual scale and in most seasons in northern China. Transportation emissions play a leading role in the four seasons for MUYR and EC in southern China, MYR and NC in northern China, and on a national scale. Compared with primary particulate matter, secondary anthropogenic precursors have a more important effect on PM$_{2.5}$ concentrations at the national or regional annual scale.

The influence mechanism of pollutants discharged by different sectors on PM$_{2.5}$ concentrations is more complicated, which also makes it difficult for us to clarify the contributions of various factors to PM$_{2.5}$ concentrations. This study comprehensively and quantitatively assessed the impact of anthropogenic emissions from various sectors and their interactions on PM$_{2.5}$ concentrations. Given the complex nonlinear relationship between PM$_{2.5}$ concentrations and its influencing factors, this study will help us better understand the impact mechanism of PM$_{2.5}$ pollution. Moreover, it will help researchers improve the accuracy of PM$_{2.5}$ prediction models and help governments formulate more precise PM$_{2.5}$ pollution control policies.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph182010869/s1, Figure S1: Ten regions in China. Figure S2: Locations of air quality monitoring stations. Figure S3: Seasonal mean PM$_{2.5}$ concentrations in spring (a), summer (b), autumn (c), and winter (d) in Chinese cities (2015–2017). Figure S4: Maps of (a) primary industry PM$_{2.5}$ emissions, (b) primary power PM$_{2.5}$ emissions, (c) primary resident PM$_{2.5}$ emissions, and (d) primary transportation PM$_{2.5}$ emissions from Chinese cities with different emission sectors in 2016 with resolution of 0.25$\degree$ × 0.25$\degree$. Figure S5: Maps of (a) agriculture NH$_3$ emissions, (b) power NH$_3$ emissions, (c) resident NH$_3$ emissions, and (d) transportation NH$_3$ emissions from Chinese cities with different emission sectors in 2016 with resolution of 0.25$\degree$ × 0.25$\degree$. Figure S6: Maps of (a) industry NH$_3$ emissions, (b) power NH$_3$ emissions, (c) resident NH$_3$ emissions, and (d) transportation NH$_3$ emissions from Chinese cities with different emission sectors in 2016 with resolution of 0.25$\degree$ × 0.25$\degree$. Figure S7: Maps of (a) industry SO$_2$ emissions, (b) power SO$_2$ emissions, (c) resident SO$_2$ emissions, and (d) transportation SO$_2$ emissions from Chinese cities with different emission sectors in 2016 with resolution of 0.25$\degree$ × 0.25$\degree$. Figure S8: Maps of (a) industry VOC$_5$ emissions, (b) power VOC$_5$ emissions, (c) resident VOC$_5$ emissions, and (d) transportation VOC$_5$ emissions from Chinese cities with different emission sectors in 2016 with resolution of 0.25$\degree$ × 0.25$\degree$. Figure S9: Annual and seasonal $q$ values of driving factors for PM$_{2.5}$ concentrations between PM$_{2.5}$ concentrations and impacting factors at the national scale (China). $P_{PM}$ denotes primary PM$_{2.5}$; NO denotes NO$_X$; VO denotes VOCs; NH denotes NH$_3$; SO denotes SO$_2$. Figure S10: Annual and seasonal $q$ values of driving factors for PM$_{2.5}$ concentrations between PM$_{2.5}$ concentrations and impacting factors at the regional scale (China). $P_{PM}$ denotes primary PM$_{2.5}$; NO denotes NO$_X$; VOCs VO denotes VOCs; NH denotes NH$_3$; SO denotes SO$_2$. Table S1: Effect of various anthropogenic factors with different emission sectors on PM$_{2.5}$ concentrations in China in 2016. Table S2: Effect of various anthropogenic factors with different emission sectors on PM$_{2.5}$ concentrations throughout the whole year at the regional scale. Table S3: Effect of various anthropogenic factors with different emission sectors on
PM$_{2.5}$ concentrations in spring at the regional scale. Table S4: Effect of various anthropogenic factors with different emission sectors on PM$_{2.5}$ concentrations in summer at the regional scale. Table S5: Effect of various anthropogenic factors with different emission sectors on PM$_{2.5}$ concentrations in autumn at the regional scale. Table S6: Effect of various anthropogenic factors with different emission sectors on PM$_{2.5}$ concentrations in winter at the regional scale.

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**Informed Consent Statement:** Informed consent obtained from all subjects or patient consent was waived are not applicable for studies not involving humans.

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**Abbreviations**

- PM$_{2.5}$: fine particulate matter
- NOx: nitrogen oxides
- VOCs: volatile organic compounds
- SO$_2$: sulfur dioxide
- NH$_3$: ammonia
- UYR: the upper zone of the Yellow River
- MUPR: the middle and upper zone of the Pearl River
- MYR: the middle zone of the Yellow River
- NC: the northern coastal zone
- NE: the northeast zone
- MUYR: the middle and upper zone of the Yangtze River
- SC: the southeast coastal zone
- XJ: the Xinjiang zone
- QTP: the Qinghai-Tibetan Plateau
- EC: the eastern coastal area

**References**

1. Jerrett, M. Atmospheric science: The death toll from air-pollution sources. *Nature* 2015, 525, 330–331. [CrossRef] [PubMed]
2. Pui, D.Y.H.; Chen, S.-C.; Zuo, Z. PM$_{2.5}$ in China: Measurements, sources, visibility and health effects, and mitigation. *Particuology* 2014, 13, 1–26. [CrossRef]
3. Watson, T. Environment: Breathing trouble. *Nature* 2014, 513, S14–S15.
4. Patz, J.A.; Campbell-Lendrum, D.; Holloway, T.; Foley, J.A. Impact of regional climate change on human health. *Nature* 2005, 438, 310–317. [CrossRef]
5. Lim, S.S.; Vos, T.; Flaxman, A.D.; Danaei, G.; Shibuya, K.; Adair-Rohani, H.; Amann, M.; Anderson, H.R.; Andrews, K.G.; Aryee, M.; et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: A systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 2012, 380, 2224–2260. [CrossRef]
6. Zhang, Q.; Zheng, Y.; Tong, D.; Shao, M.; Wang, S.; Zhang, Y.; Xu, X.; Wang, J.; He, H.; Liu, W.; et al. Drivers of improved PM$_{2.5}$ air quality in China from 2013 to 2017. *Proc. Natl. Acad. Sci. USA* 2019, 116, 24463–24469. [CrossRef]
7. Guo, S.; Hu, M.; Zamora, M.L.; Peng, J.; Shang, D.; Zheng, J.; Du, Z.; Wu, Z.; Shao, M.; Zeng, L.; et al. Elucidating severe urban haze formation in China. *Proc. Natl. Acad. Sci. USA* 2014, 111, 17373–17378. [CrossRef] [PubMed]
8. Zhang, Q.; He, K.; Huo, H. Cleaning China’s air. *Nature* 2012, 484, 161–162. [CrossRef]
9. Chen, Z.; Chen, D.; Zhao, C.; Kwan, M.P.; Cai, J.; Zhuang, Y.; Zhao, B.; Wang, X.; Chen, B.; Yang, J.; et al. Influence of meteorological conditions on PM$_{2.5}$ concentrations across China: A review of methodology and mechanism. *Environ. Int.* 2020, 139, 105558. [CrossRef]
10. Li, X.; Song, H.; Zhai, S.; Lu, S.; Kong, Y.; Xia, H.; Zhao, H. Particulate matter pollution in Chinese cities: Areal-temporal variations and their relationships with meteorological conditions (2015–2017). *Environ. Pollut.* 2019, 246, 11–18. [CrossRef]

11. Tai, A.P.K.; Mickley, L.J.; Jacob, D.J. Correlations between fine particulate matter (PM$_{2.5}$) and meteorological variables in the United States: Implications for the sensitivity of PM$_{2.5}$ to climate change. *Atmos. Environ.* 2010, 44, 3976–3984. [CrossRef]

12. Megaritis, A.G.; Fountoukis, C.; Charalampidis, P.E.; Denier Van Der Gon, H.A.C.; Pilinis, C.; Pandis, S.N. Linking climate and air quality over Europe: Effects of meteorology on PM$_{2.5}$ concentrations. *Atmos. Chem. Phys.* 2014, 14, 10283–10298. [CrossRef]

13. Mahapatra, P.S.; Sinha, P.R.; Boopathy, R.; Das, T.; Mohanty, S.; Sahu, S.C.; Gurjar, B.R. Seasonal progression of atmospheric particulate matter over an urban coastal region in peninsular India: Role of local meteorology and long-range transport. *Atmos. Res.* 2018, 199, 145–158. [CrossRef]

14. Galindo, N.; Varela, M.; Gil-Montío, J.; Yubero, E.; Nicolás, J. The Influence of Meteorology on Particulate Matter Concentrations at an Urban Mediterranean Location. *Water Air Soil Pollut.* 2011, 215, 365–372. [CrossRef]

15. Hien, P.D.; Bac, V.T.; Tham, H.C.; Nhan, D.D.; Vinh, L.D. Influence of meteorological conditions on PM$_{2.5}$ and PM$_{2.5}–10$ concentrations during the monsoon season in Hanoi, Vietnam. *Atmos. Environ.* 2002, 36, 3473–3484. [CrossRef]

16. Jacob, D.J.; Winner, D.A. Effect of climate change on air quality. *Atmos. Environ.* 2009, 43, 51–63. [CrossRef]

17. He, J.; Gong, S.; Yu, Y.; Yu, L.; Wu, L.; Mao, H.; Song, C.; Zhao, S.; Liu, H.; Li, X.; et al. Air pollution characteristics and their relation to meteorological conditions during 2014–2015 in major Chinese cities. *Environ. Pollut.* 2017, 223, 484–496. [CrossRef]

18. Li, J.; Chen, H.; Li, Z.; Wang, P.; Cribb, M.; Fan, X. Low-level temperature inversions and their effect on aerosol condensation nuclei concentrations under different large-scale synoptic circulations. *Adv. Atmos. Sci.* 2015, 32, 898–908. [CrossRef]

19. Trinh, T.T.; Trinh, T.T.; Le, T.T.; Nguyen, T.D.H.; Tu, B.M. Temperature inversion and air pollution relationship, and its effects on human health in Hanoi City, Vietnam. *Environ. Geochem. Health* 2019, 41, 929–937. [CrossRef]

20. Cheng, Y.; He, K.; Du, Z.Y.; Zheng, M.; Duan, F.K.; Ma, Y.L. Humidity plays an important role in the PM$_{2.5}$ pollution in Beijing. *Environ. Pollut.* 2015, 195, 68–75. [CrossRef]

21. Trivedi, D.K.; Ali, K.; Beig, G. Impact of meteorological parameters on the development of fine and coarse particles over Delhi. *Sci. Total Environ.* 2014, 478, 175–183. [CrossRef] [PubMed]

22. Yin, Q.; Wang, J.; Hu, M.; Wong, H. Estimation of daily PM$_{2.5}$ concentration and its relationship with meteorological conditions in Beijing. *J. Environ. Sci. (China)* 2016, 48, 161–168. [CrossRef] [PubMed]

23. Fleming, Z.L.; Monks, P.S.; Manning, A.J. Review: Uncoupling the influence of air-mass history in interpreting observed atmospheric composition. *Atmos. Res.* 2012, 104–105, 1–39. [CrossRef]

24. Guo, L.C.; Zhang, Y.; Lin, H.; Zeng, W.; Liu, T.; Xiao, J.; Rutherford, S.; You, J.; Ma, W. The washout effects of rainfall on atmospheric particulate pollution in two Chinese cities. *Environ. Pollut.* 2016, 215, 195–202. [CrossRef]

25. Li, X.; Ma, Y.; Wang, Y.; Liu, N.; Hong, Y. Temporal and spatial analyses of particulate matter (PM$_{10}$ and PM$_{2.5}$) and its relationship with meteorological parameters over an urban city in northeast China. *Atmos. Res.* 2017, 198, 185–193. [CrossRef]

26. Zheng, C.; Zhao, C.; Zhu, Y.; Wang, Y.; Shi, X.; Wu, X.; Chen, T.; Wu, F.; Qiu, Y. Analysis of influential factors for the relationship between PM$_{2.5}$ and AOD in Beijing. *Atmos. Chem. Phys.* 2017, 17, 13473–13489. [CrossRef]

27. Wu, P.; Ding, Y.; Liu, Y. Atmospheric circulation and dynamic mechanisms for persistent haze events in the Beijing–Tianjin–Hebei region. *Adv. Atmos. Sci.* 2017, 34, 429–440. [CrossRef]

28. Yang, X.; Zhao, C.; Zhou, L.; Wang, Y.; Liu, X. Distinct impact of different types of aerosols on surface solar radiation in China. *J. Geophys. Res. Atmos.* 2016, 121, 6495–6471. [CrossRef]

29. Liu, P.; Song, H.; Wang, T.; Wang, F.; Li, X.; Miao, C.; Zhao, H. Effects of meteorological conditions and anthropogenic precursors on ground-level ozone concentrations in Chinese cities. *Environ. Pollut.* 2020, 262, 114366. [CrossRef]

30. Ang-Olson, J.; Fischer, M.; Dula, R. Land Use as an Air Quality Control Measure: Review of Current Practice and Examination of Policy Options. *Transp. Res. Rec.* 2000, 1738, 33–38. [CrossRef]

31. Ooi, M.C.G.; Chan, A.; Ashfold, M.J.; Oozeer, M.Y.; Morris, K.I.; Kong, S.S.K. The role of land use on the local climate and air quality during calm inter-monsoon in a tropical city. *Geosci. Front.* 2019, 10, 405–415. [CrossRef]

32. Shi, Y.; Bilal, M.; Ho, H.C.; Omar, A. Urbanization and regional air pollution across South Asian developing countries—A nationwide land use regression for ambient PM$_{2.5}$ assessment in Pakistan. *Environ. Pollut.* 2020, 266, 115145. [CrossRef]

33. Han, L.; Zhou, W.; Li, W.; Qian, Y. Urbanization strategy and environmental changes: An insight with relationship between population change and fine particulate pollution. *Sci. Total Environ.* 2018, 642, 789–799. [CrossRef] [PubMed]

34. Ferr, M.; Sjöberg, K. Concentrations and emission factors for PM$_{2.5}$ and PM$_{10}$ from road traffic in Sweden. *Atmos. Environ.* 2015, 119, 211–219. [CrossRef]

35. Li, G.; Fang, C.; Wang, S.; Sun, S. The Effect of Economic Growth, Urbanization, and Industrialization on Fine Particulate Matter (PM$_{2.5}$) Concentrations in China. *Environ. Sci. Technol.* 2016, 50, 11452–11459. [CrossRef] [PubMed]

36. Ma, Y.R.; Ji, Q.; Fan, Y. Spatial linkage analysis of the impact of regional economic activities on PM$_{2.5}$ pollution in China. *J. Clean. Prod.* 2016, 139, 1157–1167. [CrossRef]

37. Wang, T.; Zhang, L.; Zhou, S.; Zhang, T.; Zhai, S.; Yang, Z.; Wang, D.; Song, H. Effects of ground-level ozone pollution on yield and economic losses of winter wheat in Henan, China. *Atmos. Environ.* 2021, 262, 118654. [CrossRef]

38. Blanchard, C.L.; Shaw, S.L.; Edgerton, E.S.; Schwab, J.J. Emission influences on air pollutant concentrations in New York state: II. PM$_{2.5}$ organic and elemental carbon constituents. *Atmos. Environ.* 2019, 3, 100039. [CrossRef]
39. Hsu, C.-H.; Cheng, F.-Y.; Chang, H.-Y.; Lin, N.-H. Implementation of a dynamical NH3 emissions parameterization in CMAQ for improving PM2.5 simulation in Taiwan. Atmos. Environ. 2019, 218, 116923. [CrossRef]

40. Backes, A.M.; Aulinger, A.; Bieser, J.; Matthias, V.; Quante, M. Ammonia emissions in Europe. part II: How ammonia emission abatement strategies affect secondary aerosols. Atmos. Environ. 2016, 126, 153–161. [CrossRef]

41. Bittman, S.; Jones, K.; Vingarzan, R.; Hunt, D.E.; Sheppard, S.C.; Tait, J.; So, R.; Zhao, J. Weekly agricultural emissions and ambient concentrations of ammonia: Validation of an emission inventory. Atmos. Environ. 2015, 113, 108–117. [CrossRef]

42. Trail, M.; Tsimpidi, A.P.; Liu, P.; Tsisgaridis, K.; Hu, Y.; Nenes, A.; Stone, B.; Russell, A.G. Reforestation and crop land conversion impacts on future regional air quality in the Southeastern U.S. Agric. For. Meteorol. 2015, 209–210, 78–86. [CrossRef]

43. Tao, W.T.; Liu, J.; Ban-Weiss, G.A.; Hauglustaine, D.A.; Zhang, L.; Zhang, Q.; Cheng, Y.; Yu, Y. Effects of urban land expansion on the regional meteorology and air quality of eastern China. Atmos. Chem. Phys. 2015, 15, 10299–11034. [CrossRef]

44. Kocifaj, M.; Barentine, J.C. Air pollution mitigation can reduce the brightness of the night sky in and near cities. Sci. Rep. 2021, 11, 1–10. [CrossRef]

45. Wang, X.; Tian, G.; Yang, D.; Zhang, W.; Lu, D.; Liu, Z. Responses of PM2.5 pollution to urbanization in China’s cities using spatial regression and the geographical detector technique. Sci. Total Environ. 2018, 619–620, 436–445. [CrossRef] [PubMed]

46. Sun, L.; Wei, J.; Duan, D.H.; Guo, Y.M.; Yang, D.X.; Jia, C.; Mi, X.T.; Mi, L.S.; Wei, J.; Duan, D.H.; et al. Impact of Land-Use and Land-Cover Change on urban air quality in representative cities of China. J. Atmos. Sol.-Terr. Phys. 2016, 142, 43–54. [CrossRef]

47. McCarty, J.; Kaza, N. Urban form and air quality in the United States. Landsc. Urban Plan. 2015, 139, 168–179. [CrossRef]

48. Penrod, A.; Zhang, Y.; Wang, K.; Wu, S.Y.; Leung, L.R. Impacts of future climate and emission changes on U.S. air quality. J. Environ. Manag. 2014, 89, 533–547. [CrossRef]

49. Jing, Z.; Liu, P.; Wang, T.; Song, H.; Lee, J.; Xu, T.; Xing, Y. Effects of meteorological factors and anthropogenic precursors on PM2.5 concentrations in cities in China. Sustainability 2020, 12, 3550. [CrossRef]

50. Sä, E.; Martins, H.; Ferreira, J.; Marta-Almeida, M.; Rocha, A.; Carvalho, A.; Freitas, S.; Borrego, C. Climate change and pollutant emissions impacts on air quality in 2050 over Portugal. Atmos. Environ. 2016, 131, 209–224. [CrossRef]

51. Liu, Y. A Study on Zoning “New Three Macro-Regional Development Zones” of Regional Economy of China. Acta Geogr. Sin. 2005, 60, 361–370.

52. Wang, J.; Xu, C. Geodector:principle and prospective. Acta Geogr. Sin. 2017, 72, 116–134.

53. Wang, J.F.; Zhang, T.L.; Fu, B.J. A measure of spatial stratified heterogeneity. Ecol. Indic. 2016, 67, 250–256. [CrossRef]

54. Wang, J.F.; Hu, Y. Environmental health risk detection with GeoDetector. Environ. Model. Softw. 2012, 33, 114–115. [CrossRef]

55. Wang, S.; Zhou, C.; Wang, Z.; Feng, K.; Hubacek, K. The characteristics and drivers of fine particulate matter (PM2.5) distribution in China. J. Clean. Prod. 2017, 142, 1800–1809. [CrossRef]

56. Yang, D.; Wang, X.; Xu, J.; Xu, C.; Lu, D.; Ye, C.; Wang, Z.; Bai, L. Quantifying the influence of natural and socioeconomic factors and their interactive impact on PM2.5 pollution in China. Environ. Pollut. 2018, 241, 475–483. [CrossRef]

57. Zhang, Q.; Tong, P.; Liu, M.; Lin, H.; Yun, X.; Zhang, H.; Tao, W.; Liu, J.; Wang, S.; Tao, S.; et al. A WRF-Chem model-based future vehicle emission control policy simulation and assessment for the Beijing-Tianjin-Hebei region, China. J. Environ. Manag. 2020, 253, 109751. [CrossRef]

58. Ma, T.; Duan, F.; He, K.; Qin, Y.; Tong, D.; Geng, G.; Liu, X.; Li, H.; Yang, S.; Ye, S.; et al. Air pollution characteristics and their relationship with emissions and meteorology in the Yangtze River Delta region during 2014–2016. J. Environ. Sci. 2019, 83, 8–20. [CrossRef]

59. Liu, Q.; Wang, S.; Zhang, W.; Li, J.; Dong, G. The effect of natural and anthropogenic factors on PM2.5: Empirical evidence from Chinese cities with different income levels. Sci. Total Environ. 2019, 653, 157–167. [CrossRef] [PubMed]

60. Zhu, J.L.; Denise, L.M.; Qi, C.; Qiang, Z.; Yu, S.; Wei, P.; Zbigniew, K.; Xinghua, Q.; Shiqiu, Z.; Min, H.; et al. Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source. Proc. Natl. Acad. Sci. USA 2016, 113, 7756–7761.

61. Chafe, Z.A.; Brauer, M.; Klimont, Z.; Dingenen, R.; Mehta, S.; Rao, S.; Riahi, K.; Dentener, F.; Smith, K.R. Household cooking with solid fuels contributes to ambient PM2.5 air pollution and the burden of disease. Environ. Health Perspect. 2014, 122, 1314–1320. [CrossRef]

62. Xu, Y.; Yue, W.; Lei, Y.; Huang, Q.; Zhao, Y.; Cheng, S.; Ren, Z.; Wang, J. Spatiotemporal variation in the impact of meteorological conditions on PM2.5 pollution in China from 2000 to 2017. Atmos. Environ. 2020, 223, 117215. [CrossRef]

63. Li, M.; Wang, L.; Liu, J.; Gao, W.; Song, T.; Sun, Y.; Li, L.; Li, X.; Wang, Y.; Liu, L.; et al. Exploring the regional pollution characteristics and meteorological formation mechanism of PM2.5 in North China during 2013–2017. Environ. Int. 2020, 134, 105283. [CrossRef]

64. Wu, Y.; Gu, B.; Erisman, J.W.; Reis, S.; Fang, Y.; Lu, X.; Zhang, X. PM2.5 pollution is substantially affected by ammonia emissions in China. Environ. Pollut. 2016, 218, 86–94. [CrossRef] [PubMed]

65. Li, L.; Kumar, M.; Zhu, C.; Zhong, J.; Francisco, J.S.; Zeng, X.C. Near-Barrierless Ammonium Bisulfate Formation via a Loop-Structure Promoted Proton-Transfer Mechanism on the Surface of Water. J. Am. Chem. Soc. 2016, 138, 1816–1819. [CrossRef] [PubMed]
67. Shen, G.; Ru, M.; Du, W.; Zhu, X.; Zhong, Q.; Chen, Y.; Shen, H.; Yun, X.; Meng, W.; Liu, J.; et al. Impacts of air pollutants from rural Chinese households under the rapid residential energy transition. *Nat. Commun.* 2019, 10, 1–8. [CrossRef]

68. Timmermans, R.; Kranenburg, R.; Manders, A.; Hendriks, C.; Segers, A.; Dammers, E.; Zhang, Q.; Wang, L.; Liu, Z.; Zeng, L.; et al. Source apportionment of \( \text{PM}_{2.5} \) across China using LOTOS-EUROS. *Atmos. Environ.* 2017, 164, 370–386. [CrossRef]

69. Xiao, Q.; Ma, Z.; Li, S.; Liu, Y. The impact of winter heating on air pollution in China. *PLoS ONE* 2015, 10, e0117311. [CrossRef]

70. Statistics, N.B.O. *China Energy Statistical Yearbook (2000–2012)*; China Statistics Press: Beijing, China, 2012.

71. Wang, H.; He, X.; Liang, X.; Choma, E.F.; Liu, Y.; Shan, L.; Zheng, H.; Zhang, S.; Nielsen, C.P.; Wang, S.; et al. Health benefits of on-road transportation pollution control programs in China. *Proc. Natl. Acad. Sci. USA* 2020, 117, 25370–25377. [CrossRef]

72. Wu, Y.; Zhang, S.; Hao, J.; Liu, H.; Wu, X.; Hu, J.; Walsh, M.P.; Wallington, T.J.; Zhang, K.M.; Stevanovic, S. On-road vehicle emissions and their control in China: A review and outlook. *Sci. Total Environ.* 2017, 574, 332–349. [CrossRef] [PubMed]

73. Huang, R.-J.; Zhang, Y.; Bozzetti, C.; Ho, K.-F.; Cao, J.-J.; Han, Y.; Daellenbach, K.R.; Slowik, J.G.; Platt, S.M.; Canonaco, F.; et al. High secondary aerosol contribution to particulate pollution during haze events in China. *Nature* 2014, 514, 218–222. [CrossRef]