Chin. Geogra. Sci. 2018 Vol. 28 No. 5 pp. 810–822
https://doi.org/10.1007/s11769-018-0992-0

Springer Science Press
www.springerlink.com/content/1002-0063

Spatiotemporal Variations and Influencing Factors Analysis of $PM_{2.5}$ Concentrations in Jilin Province, Northeast China

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Abstract: High $PM_{2.5}$ concentrations and frequent air pollution episodes during late autumn and winter in Jilin Province have attracted attention in recent years. To describe the spatial and temporal variations of $PM_{2.5}$ concentrations and identify the decisive influencing factors, a large amount of continuous daily $PM_{2.5}$ concentration data collected from 33 monitoring stations over 2-year period from 2015 to 2016 were analyzed. Meanwhile, the relationships were investigated between $PM_{2.5}$ concentrations and the land cover, socioeconomic and meteorological factors from the macroscopic perspective using multiple linear regressions (MLR) approach. $PM_{2.5}$ concentrations across Jilin Province averaged 49 $\mu g/m^3$, nearly 1.5 times of the Chinese annual average standard, and exhibited seasonal patterns with generally higher levels during late autumn and over the long winter than the other seasons. Jilin Province could be divided into three kinds of sub-regions according to 2-year average $PM_{2.5}$ concentration of each city. Most of the spatial variation in $PM_{2.5}$ levels could be explained by forest land area, cultivated land area, urban greening rate, coal consumption and soot emissions of cement manufacturing. In addition, daily $PM_{2.5}$ concentrations had negative correlation with daily precipitation and positive correlation with air pressure for each city, and the spread and dilution effect of wind speed on $PM_{2.5}$ was more obvious at mountainous area in Jilin Province. These results indicated that coal consumption, cement manufacturing and straw burning were the most important emission sources for the high $PM_{2.5}$ levels, while afforestation and urban greening could mitigate particulate air pollution. Meanwhile, the individual meteorological factors such as precipitation, air pressure, wind speed and temperature could influence local $PM_{2.5}$ concentration indirectly.

Keywords: particulate matter; $PM_{2.5}$; spatial variation; temporal variation; Jilin Province

Citation: WEN Xin, ZHANG Pingyu, LIU Daqian, 2018. Spatiotemporal Variations and Influencing Factors Analysis of $PM_{2.5}$ Concentrations in Jilin Province, Northeast China. *Chinese Geographical Science*, 28(5): 810–822. https://doi.org/10.1007/s11769-018-0992-0

1 Introduction

With rapid economic growth, industrialization and urbanization, China has experienced a severe air pollution problem which has been recognized as a major concern. The concentrations of particulate matter with an aerodynamic diameter of 2.5μm or smaller ($PM_{2.5}$) have attracted special attention due to the high levels, as well as its associations with adverse effects on human health (Adamkiewicz et al., 2014; Zwozdziak et al., 2016; Wang et al., 2017) and ecosystem (Chen et al., 2014; Zhai et al., 2014; Li et al., 2015). Therefore, many regulations, standards and monitoring measures have been prioritized to control $PM_{2.5}$ emission. For example, the Chinese government released the latest Ambient Air Quality Standards (Ministry of Environmental Protection, 2012) that established ambient $PM_{2.5}$ standards for the first time in 2012. Moreover, a nation-wide air quality monitoring network has been operating in China to monitor air pollutants automatically, and the network has expanded to 1436 sites spread over 338 cities in 2016 from 550 sites in 74 cities since 2013. Addition-

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Received date: 2018-02-02; accepted date: 2018-05-31
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 41601607, 41771138, 41771161), Strategic Planning Project from Institute of Northeast Geography and Agroecology (IGA), Chinese Academy of Sciences (No. Y6H2091001-3)
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ally, 'Plan of Action for Preventing and Controlling of Atmospheric Pollution' (State Council of China, 2013) with many measures has adopted to reduce $PM_{2.5}$ levels. With the implementation of these effective air pollution controls, the $PM_{2.5}$ concentration is decreasing gradually in recent years, however, the number of days with $PM_{2.5}$ as the main pollutant still accounted for 80.3% among the heavily and ultra-seriously polluted days in 338 Chinese cities in 2016 (Ministry of Environmental Protection, 2017). Consequently, there is a nationwide research focus on $PM_{2.5}$ as the principal pollutant in China, including its distribution, fluctuation pattern, main sources and other characteristics. Most studies have focused on the northern China (Wang et al., 2015b; Yao, 2017), the Yangtze River delta (Hua et al., 2015; Ma et al., 2016) and the Pearl River delta (Song et al., 2014; Lai et al., 2016).

Severe haze episodes observed recently over Northeast China corresponded to proximately 2–3 times of the historical air pollution (Wang et al., 2014; Yang et al., 2017), especially during late autumn and over the long winter (Chen et al., 2017; Fang et al., 2017; Ma et al., 2017). The proportion of area whose $PM_{2.5}$ concentrations exceeded the Grade II standard limit of 35 $\mu g/m^3$ (is equivalent to WHO Interim Target-1) increased annually in the past decade (Luo et al., 2017). Northeast China has ranked fifth in terms of the most severe air pollution region in China (Bao et al., 2015). From the microcosmic perspective, a number of studies have been dedicated to investigating the physical, chemical and optical properties to find the source apportionment of $PM_{2.5}$ in Northeast China by analyzing the abundance of ionic/inorganic elements, organic carbon (OC), elemental carbon (EC), mineral dust elements and so on (Zhao et al., 2013; Zhang et al., 2014). Most explorations mainly focused on one single large city, such as Harbin, Changchun and Shenyang (Huang et al., 2010; Zhao et al. 2013; Chen et al., 2015, 2017; Fang et al., 2017), and were mostly at a specific time spot (Han et al., 2010; Li et al., 2015a; Zhao et al., 2017; Yang et al., 2017). Whereas few studies emphasized multi-cities or at a long time scale from the macroscopic perspective.

Recent studies indicate that the spatial extent of PM pollution has been expanding to broader regional scales (Liu et al., 2013; Hu et al., 2014; Chen et al., 2017), this trend urges needs for large-scale ambient $PM_{2.5}$ to design effective control strategies. Jilin Province, located at the center of Northeast China, has longstanding industry and is an important agricultural base. Additionally, Jilin Province has a long winter requiring heating of buildings emitting pollution into the air. The topography of Jilin Province is high in the east with mountainous area and low in the midland and west with plain and meadow area. These factors contribute to the complexity of different emission sources and diffusion of $PM_{2.5}$. Therefore, it is necessary to comprehensively investigate the spatial and temporal variations and the decisive influence factors on $PM_{2.5}$ concentrations for the purpose of providing a more reliable research basis for valid control measures.

This study described the spatial and temporal variations of $PM_{2.5}$ in Jilin Province by analyzing a large amount of continuous daily $PM_{2.5}$ concentration data collected from 33 monitoring stations over 2-year period from 2015 to 2016. Another primary objective of our study was to identify the decisive influencing factors, including land cover, socioeconomic and meteorological factors on $PM_{2.5}$ levels using multiple linear regression (MLR) approach. In brief, this study has two main contributions. First, this research attempt to investigate the relationships between $PM_{2.5}$ concentrations and the land cover, socioeconomic and meteorological factors by statistical method from the macroscopic perspective. Second, we analyzed the spatiotemporal patterns of $PM_{2.5}$ concentrations at a regional scale to fully consider the spatial heterogeneity of $PM_{2.5}$ and at a long time scale. The results of this study are conducive to make appropriate strategies and take effective measures on local $PM_{2.5}$ pollution control.

2 Materials and Methods

2.1 Study area

Jilin Province (40°50'–46°19'N, 121°38'–131°19'E) is located at the center of Northeast China, and it occupies an area of 187 400 km^2 with the population of 26.62 million at the end of 2015 (Bureau of Statistics of Jilin Province, 2016). Cities, including county-level, prefectural-level cities and municipalities are the basic administrative units which can be used to reveal Chinese Mainland's natural geographic features and socioeconomic condition, as well as its air pollution. Additionally, natural geographic factors and socioeconomic factors match well with the $PM_{2.5}$ concentrations distribution at the city level. Therefore, nine prefectural-level cities were used as the basic study unit to explore the influencing factors of $PM_{2.5}$. Jilin Province is divided into three geographical subareas according to the terrain and the major function: the east is mountainous area which includes three cities of Baishan, Tonghua and Yanbian, and it is the green transformation development area; the midland is plain area which includes five cities of Changchun, Jilin, Siping and Liaoyuan, and it is the core area of innovation transformation; the west is meadow area which includes Songyuan and Baicheng, and it is the ecological economic area.

In Jilin Province, central heating is provided for cities during around November to March. Thus this period is commonly categorized as winter for this region. According to the characteristics of high temperature, the period from June to August is defined as the summer. Accordingly, spring is defined as the period from April to May whilst autumn is defined as the period between September and October. The criteria for categorizing four seasons are consistent with a common phenomenon in Jilin Province, which is described as 'The spring and autumn in Jilin Province hardly last long'.

2.2 Data source and description

Multisource data were used in this study, which were classified into four categories as follow. Information from the 33 state-controlled ambient air quality monitoring stations across Jilin Province in the China National Air Quality Monitoring Network was utilized. These stations all use TEOMs plus FDMS which is real-time air quality system (AQS). Each of the nine cities contains at least two state-controlled monitors. The station B1 and B11 are defined as contrast sites to reflect the air quality unaffected by urban pollution, and the remaining 31 sites are urban sites, these stations scatter from the east to the west of Jilin Province, covering all the prefecture-level cities, most of the spatial regions and typical land types in Jilin Province (Fig. 1). Due to equipment failure or internet error, few data were missing. Few data were also rejected due to anomalous measurements. Jilin Province-wide daily average concentration was calculated if at least 25 sites had valid daily concentrations, and the daily concentration for each city was calculated by averaging all available local stations (contrast sites B1 and B11 were excluded from the average).

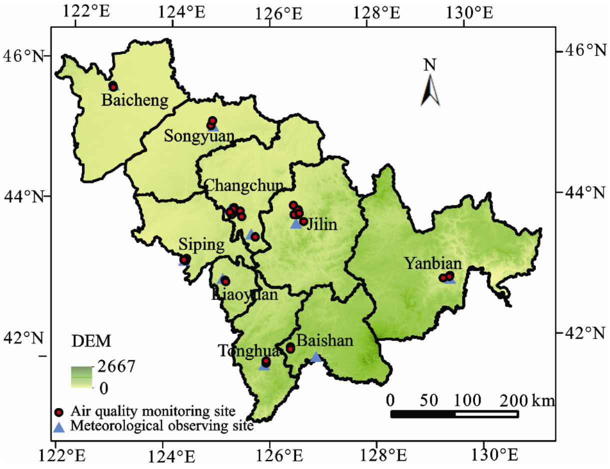

Fig. 1 Locations of the air quality monitoring stations and meteorological stations in Jilin Province

Land cover data were obtained from Department of Land and Resources of Jilin Province, which included cultivated land area, garden plot area, forest land area, grassland area, urban and industrial land area, transport-related land area, water area and urban greening rate.

Socioeconomic data regarding the scale and intensity of anthropogenic activities were obtained from Bureau of Statistics of Jilin Province. Among them, per capita GDP and population density are common indicators of socioeconomic development. Furthermore, the other indicators represent the different sources and intensity of $PM_{2.5}$, including coal consumption, area of heat-supply service, the number of small inefficient coal-fired boilers, number of motor vehicles, building construction area, soot emissions of thermal power, soot emissions of cement manufacturing and soot emissions of iron-steel smelting.

Daily meteorological data were obtained from the Chinese Meteorological Data Net. The meteorological variables include air temperature, ground surface temperature, precipitation, sunshine duration, relative humidity, air pressure, and wind speed.

2.3 Statistical analyses

After checking and cleaning, the data were summarized using descriptive statistics and trend plots to evaluate the spatial and temporal characteristics of $PM_{2.5}$ exposures.

Multiple linear regression (MLR) approach (Tai et al., 2010) was used to correlate $PM_{2.5}$ concentrations to the land cover, socioeconomic and meteorological variables.

Unlike a correlation coefficient from a single linear regression, MLR allows for analysis of multiple independent variables affecting the dependent variable ($PM_{2.5}$ concentrations) at the same time. The model is of the form:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \text{interaction terms} \qquad (1)$$

where the dependent variable y represents $PM_{2.5}$ concentrations (annual or daily mean) and is a function of the coefficient β_0 (y-intercept); β_i are the regression coefficients; x_i are independent variables; i represents the i-th independent variable; n is the number of the independent variables; interaction terms, which refer to the product of two or more independent variables and represent the higher-order linear effects when variables are interacting with each other in affecting $PM_{2.5}$, are found to be small and thus excluded from the analysis. Each of the independent variables x_i represents a variable that determines the values of y, or the $PM_{2.5}$ concentrations. The regression coefficients β_i represent the amount of change in $PM_{2.5}$ concentrations for a unit change in the variables x_i if all the other variables x are held constant. These values can be interpreted as 'sensitivities' of $PM_{2.5}$ to a change in the variables. Positive coefficients refer to an increase in $PM_{2.5}$ concentrations for an increase in the variable (positive correlation), whereas negative values refer to decreases in $PM_{2.5}$ (negative correlation); Multiple correlation coefficient (R) quantifies the fitting effect of the MLR model. Simple correlation coefficients (r_i) reflects the correlation between each independent variable and the dependent variable.

Firstly, land cover and socioeconomic factors potentially associated with the spatial variation of $PM_{2.5}$ concentrations were investigated by multiple linear regression models. Eighteen variables (x_1, …, x_{18}) were chosen for inclusion in the MLR model: forest land area (ha), cultivated land area (ha), garden plot area (ha), grassland area (ha), urban and industrial land area (ha), transport-related land area (ha), water area (ha), urban greening rate (%), per capita GDP (yuan (RMB)), population density (people/km^2), coal consumption (10 000 t), area of heat-supply service (10 000 m^2), the number of small inefficient coal-fired boilers (unit), number of motor vehicles (million unit), building construction area (m^2), soot emissions of thermal power (t), soot emissions of cement manufacturing (t) and soot emissions of iron-steel smelting (t). Both land cover, socioeconomic variables and $PM_{2.5}$ concentrations were 2-year averages.

Secondly, relationships between daily meteorological factors and the temporal variation of daily $PM_{2.5}$ levels among the cities were evaluated, again using multiple regression models. We chose seven meteorological variables (x_1, …, x_7) for inclusion in the MLR model: air temperature (0.1℃), ground surface temperature (0.1 ℃), precipitation (0.1 mm), sunshine duration (0.1 h), relative humidity (1%), air pressure (0.1 hPa) and wind speed (0.1 m/s). Both the meteorological variables and $PM_{2.5}$ concentrations were daily averages.

3 Results and discussion

3.1 Overview of $PM_{2.5}$ levels

Daily $PM_{2.5}$ concentrations at the 33 sites, 9 cites and Jilin Province-wide over the period of 2015–2016 are summarized in Table 1. Data integrity was very high, all stations had over 95% valid daily observations.

At individual sites, daily average concentrations varied greatly, ranging from 2 to 733 μg/m^3, and 2-year average concentrations from 32 to 60 μg/m^3. Mean concentrations exceeded medians, showing right-skewed distributions with several extremely high values and large standard deviations. Table 1 applies the Grade-II standards (same limit values as WHO Interim Target-1) with daily and annual $PM_{2.5}$ limits of 75 and 35μg/m^3, respectively. The annual standard was exceeded at all sites except B11, B32 and B33, and the daily standard was exceeded from 6% (site B33) to 23% (site B14 and B19) of days.

Using the Chinese classifications of the air quality (Fig. 2), the cities in Jilin Province experienced ultra-serious pollution on 0.1%–1.1% of days, heavy pollution on 0.5%–3.6% of days, moderate pollution on 1.5%–4.9% of days, light pollution on 5.6%–15.3% of days, favorable and excellent occupied 79.8%–91.1% days. Although most days of the study were under low and medium pollution level, highly polluted days also occupied a considerable part of the period and the degree of exceeding standard is high, to which special attention should be given.

$PM_{2.5}$ concentrations across Jilin Province averaged 49μg/m^3, nearly 1.5 times of the Chinese annual average

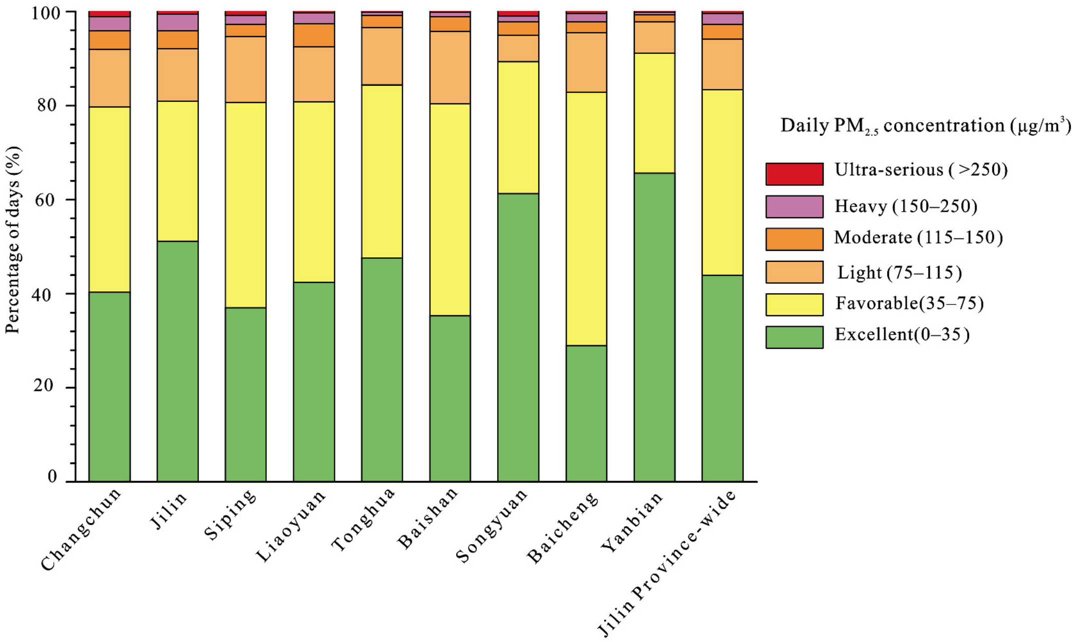

Fig. 2 Classification of days by daily $PM_{2.5}$ air quality levels of each cities in Jilin Province. In China, air quality is considered 'excellent' if daily average concentrations of $PM_{2.5}$ are below 35 μg/m^3, 'favorable' for concentrations between 35 and 75 μg/m^3, and 'polluted' for concentrations above 75 μg/m^3. When polluted, concentrations below 115 μg/m^3 are termed 'light' pollution, 115–150 μg/m^3 are 'moderate' pollution, 150–250 μg/m^3 are 'heavy' pollution, and concentrations above 250 μg/m^3 are 'ultra-serious' pollution

standard, and were several times higher than levels in cities in Europe and the United States (Chow et al., 2006; Barmpadimos et al., 2012). However, Jilin Province have implemented a number of air pollution control measures, e.g., emissions have been reduced by switching coal-fired boilers to cleaner fuels, shuttering other coal-fired plants, eliminating 'yellow-label' and outdated vehicles, and switching coal residential heating to electricity. A decline in $PM_{2.5}$ concentrations has been reported in recent years. More recently, annual average $PM_{2.5}$ concentrations of Changchun, the provincial capital of Jilin Province, have fallen from 190μg/m^3 to 46μg/m^3 during 2013 and 2016, Jilin Province -wide estimates in our study are consistent with this downward trend.

3.2 Spatiotemporal variation of $PM_{2.5}$ concentrations

Daily $PM_{2.5}$ levels of Jilin Province-wide varied considerably, it rose and dropped rapidly with sharp peaks and deep valleys appearing alternately, as shown in Fig.3. Notable seasonal variations could be seen in each city from Fig. 4. Daily $PM_{2.5}$ concentrations were relatively lower and reached Grade-II standard for almost all days between April and September. In contrast, 94% of the pollution days (daily $PM_{2.5}$ concentration > 75 μg/m^3) occurred during from October to the next year's March (pollution months), which were in late autumn and over the long winter. The gross $PM_{2.5}$ levels during this period contributed 69% to the total mass concentration. Thus the annual $PM_{2.5}$ quality is mostly determined by the $PM_{2.5}$ levels on the pollution months. In particular, the mean $PM_{2.5}$ concentrations on November, December and January averaged from 2015 to 2016 were 87, 84 and 78μg/m^3, higher than the 2-year average concentration by 73.5%, 67.8% and 56.1%, respectively. And 60% of the heavy and ultra-serious pollution incident (daily $PM_{2.5}$ concentrations > 150 μg/m^3) occurred on these three months.

According to 2-years average $PM_{2.5}$ concentration of each city, Jilin Province could be divided into three kinds of sub-regions, as shown in Fig. 5. Slightly polluted region with low $PM_{2.5}$ level (under the Grade II standard limit of 35μg/m^3) only included Yanbian which is located at the eastern mountainous area. There were three main clusters of moderately polluted regions whose $PM_{2.5}$ levels were from 35 to 55 μg/m^3, spreading across the eastern mountainous area (Baishan and

Table 1 Summary of daily $PM_{2.5}$ concentrations at the 33 monitoring stations and 9 cities of Jilin Province

City/Station	Average $PM_{2.5}$ concentration ($\mu g/m^3$)						Percentage of days attaining standards, targets, or goals (%)				
	Mean	SD	Min	Med	Max	NOBs	Grade I	Grade II/IT-1	IT-2	IT-3	AQG
Changchun	56	52	6	41	507	731	41	80	24	5	1
B1	50	48	4	34	390	705	52	81	38	18	7
B2	57	49	6	43	508	725	39	79	20	4	1
B3	60	58	6	46	625	719	34	78	19	4	1
B4	57	49	5	43	413	717	39	79	22	6	1
B5	58	50	8	43	444	718	39	78	21	5	1
B6	54	52	6	39	562	729	44	81	26	8	2
B7	46	46	4	32	435	722	55	85	37	17	6
B8	53	56	5	38	698	714	47	82	31	11	3
B9	59	70	7	42	733	728	41	79	25	7	1
B10	60	58	6	43	602	713	39	78	23	7	1
Jilin	51	46	6	34	470	731	51	81	30	7	1
B11	35	33	2	26	493	720	66	92	49	24	11
B12	53	47	5	38	443	723	46	81	26	6	2
B13	41	35	3	28	237	724	60	88	44	16	5
B14	58	53	7	39	496	721	45	77	25	6	2
B15	50	46	4	33	522	720	52	82	34	11	3
B16	48	40	7	35	447	724	51	84	30	9	2
B17	56	57	6	36	443	722	50	80	31	10	2
Siping	55	43	5	42	569	731	37	81	20	2	0
B18	53	42	5	41	528	727	41	82	24	7	1
B19	59	47	7	46	634	730	32	77	14	1	0
B20	52	43	4	40	544	731	43	83	24	6	1
Liaoyuan	52	39	4	40	367	731	43	81	26	5	1
B21	51	37	4	40	355	717	44	82	27	6	1
B22	53	42	3	40	378	720	45	79	27	7	1
Tonghua	46	31	4	36	311	731	49	84	27	6	1
B23	43	30	4	33	297	697	54	88	31	8	2
B24	49	34	3	38	324	707	46	82	26	6	1
Baishan	51	30	8	43	267	731	36	81	15	2	0
B25	49	31	4	40	252	731	42	83	22	4	1
B26	54	31	11	45	282	726	33	80	13	1	0
Songyuan	41	46	4	28	512	731	62	89	45	20	7
B27	41	44	4	28	456	723	60	89	43	19	7
B28	41	49	5	27	568	726	63	89	48	21	9
Baicheng	53	33	13	43	305	731	31	83	7	0	0
B29	52	32	3	42	309	721	33	86	8	0	0
B30	55	34	13	44	301	729	29	81	8	0	0
Yanbian	34	28	4	25	300	731	66	91	52	23	9
B31	37	33	3	26	343	731	63	88	49	22	8
B32	33	28	2	23	308	730	68	92	54	28	12
B33	32	27	4	24	249	723	69	94	53	25	11
Jilin Province	49	37	7	38	334	731	45	84	24	2	0

Notes: NOBs is number of valid observations. Grade I ($35\mu g/m^3$) and Grade II ($75\mu g/m^3$) standards refer to daily $PM_{2.5}$ concentration limit in the China Ambient Air Quality Standards (GB 3095-2012). IT-1($75\mu g/m^3$), IT-2 ($25\mu g/m^3$), IT-3 and AQG ($10\mu g/m^3$) refer to the WHO interim targets and air quality guideline of daily $PM_{2.5}$ concentration limit

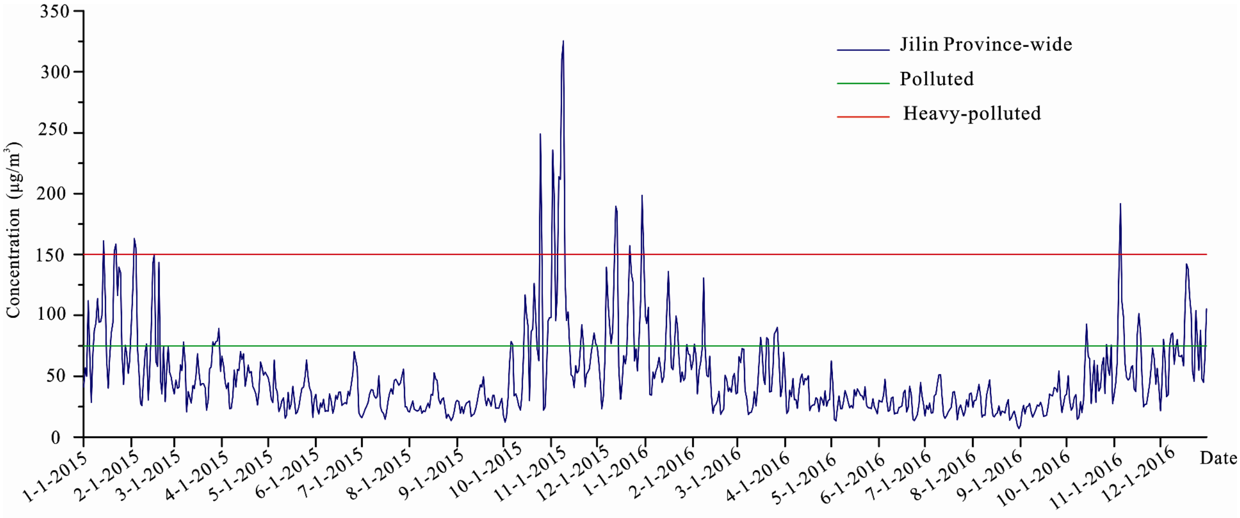

Fig. 3 Trends of daily Jilin Province-wide $PM_{2.5}$ concentrations from 2015 to 2016. Lines show daily limits of 75 and 250 μg/m^3 corresponding to classifications of 'polluted' and 'heavy-polluted' days

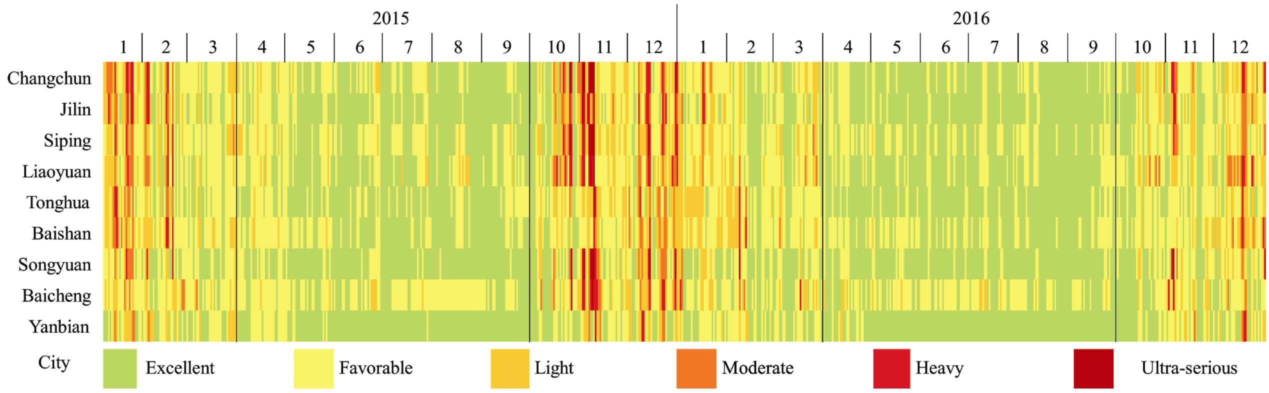

Fig. 4 Trends of daily $PM_{2.5}$ concentrations of each city from 2015 to 2016. Classification of daily $PM_{2.5}$ levels is the same as Fig. 2.

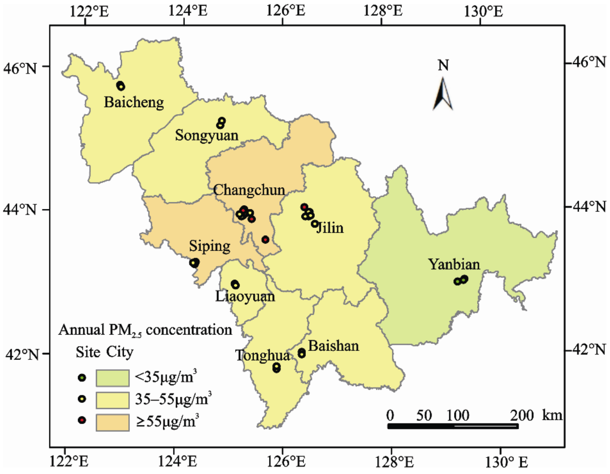

Fig. 5 Spatial distribution of annual $PM_{2.5}$ concentration for different sites and cities in Jilin Province.

Tonghua), central plain area (Jilin and Liaoyuan) and western meadow area (Songyuan and Baicheng). Besides, heavily polluted regions with high $PM_{2.5}$ level (over 55μg/m^3) included Changchun and Siping located at the central plain area. The reasons and influencing factors for the formation of the three sub-regions in $PM_{2.5}$ levels were analyzed in the next section.

3.3 Land cover and socioeconomic factors correlated with $PM_{2.5}$ concentrations

$PM_{2.5}$ concentrations have been associated with several types of land cover and the intensity of anthropogenic activities (Wu et al., 2015). In order to identify the decisive factors of spatial variation for $PM_{2.5}$ concentrations in Jilin Province, multiple linear regression (MLR) model was carried out between $PM_{2.5}$ concentrations and the latent factors mentioned above. Overall, of the eighteen factors examined, five were significantly associated with the spatial variation of $PM_{2.5}$ levels, including three land cover factors and two socioeconomic factors, they were forest land area, cultivated land area, green area per capita, coal consumption and soot emissions of cement manufacturing, respectively. These five factors may contribute to explain the spatial variation across Jilin Province in certain degree. They were collapsed to a multiple linear regression model:

$$y = 54.822 - 2.734e - 5x_1 + 3.823e - 6x_2 - 28.503x_8 + 0.01x_{11} + 0.03x_{17}$$

$$R^2 = 0.734, abjusted\ R^2 = 0.638 \qquad (2)$$

where y was 2-year average $PM_{2.5}$ level in site (μg/m^3), x_1 was forest land area (ha), x_2 was cultivated land area (ha), x_8 was urban greening rate (%), x_{11} was coal consumption (10 000 t), x_{17} was soot emissions of cement manufacturing (t).

The results indicated that $PM_{2.5}$ concentrations were negatively correlated to forest land area ($r = –0.603$) and urban greening rate ($r = –0.249$). Previous studies have shown that vegetation (particularly trees) can mitigate particulate air pollution through a number of mechanisms, such as capturing, intercepting and accumulating atmospheric particles through leaf pubescence and stomata (Beckett et al., 2000; Irga et al., 2015; Chen et al., 2016), and areas with a high fraction of vegetation may have fewer sources of emissions, e.g. industry and major roads. The forest land area of Yanbin is 3.63 million ha, accounting for 41% of the whole Jilin Province. The clean-up effect of the widespread forest contributed to the low $PM_{2.5}$ levels in Yanbin which was the only region meeting the Grade II standard limit.

A positive correlation was found between cultivated land area and $PM_{2.5}$ concentrations, with a correlation coefficient of 0.428. Cultivated land has both positive and negative effects. On the one hand, as a part of urban green space, it can reduce the $PM_{2.5}$ concentration effectively by the leaves just like ordinary vegetation. On the other hand, the smoke produced by straw burning after the harvesting of farmland is the main reason for the high concentration of $PM_{2.5}$ in autumn and winter (Ding et al., 2013). Additionally, most cultivated land is equivalent to bare land when they are fallow fields in winter. Therefore, the impact of cultivated land on $PM_{2.5}$ depends on the strength of the both factor above. And this study showed that the effect of straw burning was more obvious in Jilin Province. Fig. 6 is the burning point distribution of Jilin Province in 2015 and 2016 monitored by Fire Information for Resource Management System (FIRMS). As shown in Fig. 6 and Table1, the densest burning points were mainly distributed in Changchun and Siping whose 2-year average $PM_{2.5}$ concentration was the highest. In the moderately polluted regions, burning points were widely distributed in Baicheng and Songyuan. It implied straw burning was an important source of $PM_{2.5}$ in plain and meadow areas of Jilin Province. Chen *et al.* have found that the development of agricultural PM inventories from soil tillage and straw burning is prioritized to support air quality modeling at an agricultural site (Chen et al., 2017), which is consistent with the result of this study. Particulate matter and gaseous pollutants emitted from agricultural operations may initially change the air quality in a rural area and then affect adjacent towns/cities by diffusion. Additionally, the amount and density of burning points decreased significantly during 2015-2016, illustrating that more strict actions had taken to forbid straw-burning for controlling $PM_{2.5}$ concentrations in Jilin Province. The results also indicated that there was a significantly positive correlation between coal consumption, soot emissions of cement manufacturing and $PM_{2.5}$ concentrations. The correlation coefficients were 0.453 and 0.590, respectively. It implies that coal consumption and cement manufacturing were another two important $PM_{2.5}$ source.

As Fig. 4 shown, most of the heavy and ultra-serious pollution days (daily $PM_{2.5}$ concentrations > 150 μg/m^3) occurred on November, December and January in which temperature was the lowest and the heating energy consumption was the largest. In particular, combustion aerosol was main conclusive factors of $PM_{2.5}$ concentrations (Ding et al., 2013). The notably deteriorated air quality in winter mainly attribute to the central heating by burning coal materials, and thus leads to extra emission of airborne pollutants. The coal consumption of Changchun was 23.89 million tons in 2015 and was 23% of the total in Jilin Province, large amount of coal combustion was one of the major causes for the serious $PM_{2.5}$ pollution in Changchun. In the moderately polluted regions, Jilin and Baishan were also the large coal consumption areas with 22.57 million and 13.73 million in 2015, respectively.

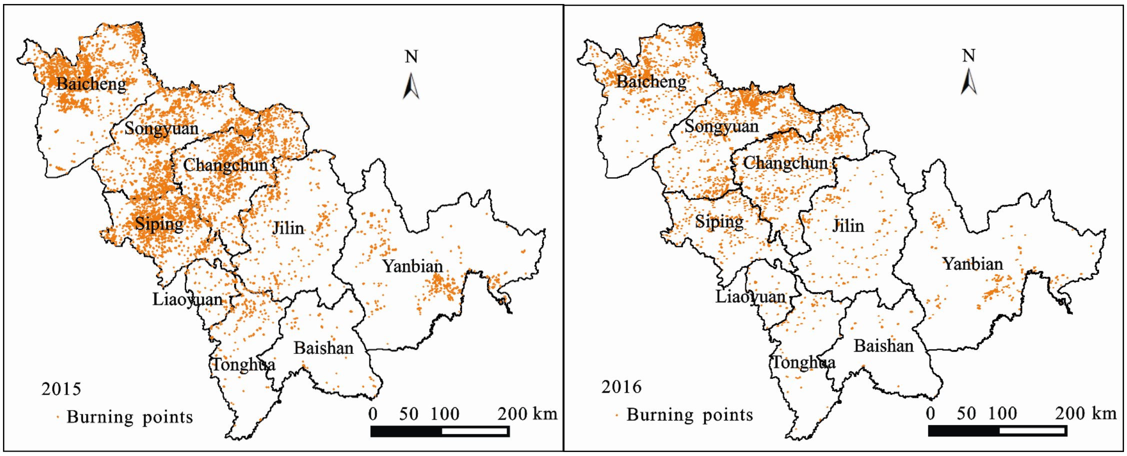

Fig. 6 The burning point distribution of Jilin Province in 2015 and 2016 monitored by Fire Information for Resource Management System (FIRMS)

The semi-finished products and finished products of cement industry are mostly in the form of powder, and accompanied by the combustion process, so its cumulative volume of PM is relatively large. The soot emissions of cement manufacturing in Siping and Changchun was 7503 and 7025 tons in 2015, accounting for 29% and 27% of the total in Jilin Province, respectively, which was one of the major reasons for the heavily polluted regions. In the moderately polluted regions, Jilin and Liaoyuan also had large soot emissions of cement manufacturing with 3636 and 3418 tons in 2015, accounting for 14% and 13% of the total, respectively.

3.4 Relationship between meteorological factors and $PM_{2.5}$ concentrations

To comprehensively analyze the role of meteorological factors for each city in affecting local $PM_{2.5}$ concentration, a set of factors were selected as follows: air temperature (TEM), ground surface temperature(GST), precipitation (PRE), sunshine duration (SSD), relative humidity (RHU), air pressure (PRS), wind speed (WIN). By analyzing two time-series variables through multiple linear regression, meteorological factors strongly correlated with daily $PM_{2.5}$ concentration were extracted for each city (Table 2). The results indicated that the existence of a significant correlation between daily $PM_{2.5}$ concentrations and daily precipitation, sunshine duration, air pressure for each city. Meanwhile, the correlations among air temperature, ground surface temperature, wind speed and $PM_{2.5}$ concentrations were only found in some cities. In contrast, there was no apparent correlation between relative humidity and $PM_{2.5}$ concentration for any city.

Precipitation amounts had negative correlation with $PM_{2.5}$ levels for each city. There are three main impacts of precipitation on $PM_{2.5}$. One is that wash-out, adsorption and collision of raindrops upon $PM_{2.5}$ resulting in the wet sedimentation of $PM_{2.5}$. The other is that after rainy weather $PM_{2.5}$ concentrations significantly decrease due to the notable reducing of dust and fugitive dust which previously suspended in the atmosphere. Additionally, surface wetting will inhibit entrainment of surface dust from roads and fields (Li et al., 2015).

Sunshine duration and the daily PM2.5 concentrations were negatively correlated, agreeing with earlier study case in other cities of China (Zhang et al., 2015). Days with extensive sunshine are typically associated with conditions which is favorable for pollutant dispersion, e.g., unstable conditions. However, high $PM_{2.5}$ levels increase light extinction and reduce insolation intensity, which can decrease the number of hours classified as sunny (Batterman et al., 2016). Thus, this variable may not be independent of explaining the daily variation of $PM_{2.5}$ level, we removed sunshine from explaining the daily variation of $PM_{2.5}$.

A positive correlation was found between air pressure and $PM_{2.5}$ concentrations. This is due to the fact that when there was high pressure, the down draft hinders the upward movement of $PM_{2.5}$, causing an accumulation of particles.

Specifically, there was a negative relation between air temperature and $PM_{2.5}$ concentrations for Jilin, Baishan, Yanbian and Songyuan. And $PM_{2.5}$ concentrations display a negative correlation with ground surface

Table 2　The correlation coefficient between the meteorological factors and $PM_{2.5}$ concentration

City	Meteorological factors						
	PRS	SSD	PRE	GST	TEM	WIN	RHU
Changchun	0.388, 0.000	–0.283, 0.000	–0.162, 0.000	–	–	–	–
Jilin	0.498, 0.000	–0.260, 0.000	–0.168, 0.024	–	–0.478, 0.020	–0.028, 0.005	–
Siping	0.403, 0.000	–0.199, 0.000	–0.151, 0.029	–	–	–	–
Liaoyuan	0.476, 0.000	–0.217, 0.000	–0.189, 0.001	–0.443, 0.041	–	–	–
Tonghua	0.528, 0.000	–0.206, 0.000	–0.169, 0.001	–0.553, 0.000	–	–0.377, 0.000	–
Baishan	0.505, 0.026	–0.188, 0.000	–0.189, 0.001	–	–0.573, 0.000	–0.244, 0.027	–
Songyuan	0.340, 0.012	–0.299, 0.000	–0.103, 0.011	–	–0.362, 0.018	–	–
Baicheng	0.208, 0.003	–0.265, 0.000	–0.063, 0.003	–	–	–	–
Yanbian	0.449, 0.019	–0.190, 0.000	–0.156, 0.022	–0.487, 0.000	–0.469, 0.022	–0.278, 0.000	–

Notes: The first value in each cell of the table presents the zero-order correlations (simple correlation coefficient r_i) between each meteorological factor and $PM_{2.5}$ concentration; the second value presents the corresponding p-value. PRS, SSD, PRE, GST, TEM, WIN and RHU refer to air pressure, sunshine duration, precipitation, ground surface temperature, air temperature, wind speed and relative humidity, respectively

temperature for Liaoyuan, Tonghua and Yanbian. Temperature can affect particulate matter by several mechanisms: fuel use associated with heating increases at low temperatures; when temperature rises, air convection becomes quick and frequent, which leads to the diffusion and dilution of $PM_{2.5}$, decreasing $PM_{2.5}$ concentrations, and vice versa (Luo et al., 2017); and formation rates of secondary aerosols increase with temperature. Given these competing factors, it was not surprisingly that different cities showed varying relationships between $PM_{2.5}$ concentrations and temperature. Negative correlations were also found during summer in Shijiazhuang (Li et al., 2015) and a positive correlation was found in winter and spring in Beijing (Zhao et al., 2014).

There was a negative correlation between wind speed and $PM_{2.5}$ concentrations for Jilin, Tonghua, Baishan and Yanbian which were located at or near by mountainous area. Higher wind speed can favor plume spread and dilution which is conducive to the diffusion of $PM_{2.5}$, resulting in lower concentrations of $PM_{2.5}$. The results indicated that the spread and dilution effect of wind speed on $PM_{2.5}$ was more obvious at mountainous area in Jilin Province.

4　Conclusions

The frequent air pollution episodes during late autumn and winter in Jilin Province in recent years warrant attention and analysis. This study examined spatial and temporal variability of $PM_{2.5}$ in Jilin Province and investigated the causes of severe $PM_{2.5}$ mass from the macroscopic perspective, emphasizing daily data collected over a recent 2-year period. $PM_{2.5}$ concentrations across Jilin Province averaged 49μg/m^3, nearly 1.5 times of the Chinese annual average standard. The $PM_{2.5}$ concentrations exhibited seasonal patterns, which were generally higher during late autumn and over the long winter, and were lower in spring, summer and early autumn. Jilin Province could be divided into three kinds of sub-regions according to 2-year average $PM_{2.5}$ concentration of each city: slightly polluted region with low $PM_{2.5}$ level only included Yanbian which is located at the eastern mountainous area; there were three main clusters of moderately polluted regions whose $PM_{2.5}$ levels were from 35 to 55 μg/m^3, spreading across the eastern mountainous area (Baishan and Tonghua), central plain area (Jilin and Liaoyuan) and western meadow area (Songyuan and Baicheng). Besides, heavily polluted regions with high $PM_{2.5}$ level (over 55μg/m^3) included Changchun and Siping located at the central plain area. Most of the spatial variation in $PM_{2.5}$ levels could be explained by forest land area, cultivated land area, urban greening rate, coal consumption and soot emissions of cement manufacturing. In addition, daily $PM_{2.5}$ concentrations had negative correlation with daily precipitation and positive correlation with air pressure for each city, and the spread and dilution effect of wind speed on $PM_{2.5}$ was more obvious at mountainous area in Jilin Province.

These results indicated that coal consumption, cement manufacturing and straw burning were the most important emission sources for the high $PM_{2.5}$ levels, while afforestation and urban greening could mitigate particulate air pollution. Meanwhile, the individual meteorological factors such as precipitation, air pressure, wind speed and temperature could influence local $PM_{2.5}$ concentration indirectly. To mitigate $PM_{2.5}$ concentrations, the following suggestions are proposed based on our study. Firstly, the improvement of fuel quality and the replacement of coal with cleaner renewable energy sources (e.g., solar energy, hydrogen fuel, biomass energy) are the most effective means of reducing $PM_{2.5}$ emissions. Regional central heating in winter is a substantial measure of the prevention and control of urban $PM_{2.5}$. Secondly, it is urgent to take measures to strictly forbid straw-burning during the late autumn at farmland. Thirdly, installing desulphurization and dust removal device for cement manufacturing industry. Last but not the least, designing of vegetation configuration based on local conditions to achieve the goal of increasing vegetation coverage.

This analysis has several limitations: the models and datasets used in this study reflected an integration of multiple scales, which would inevitably generate uncertainties in spatial statistics; the metrics are only indirect and approximate surrogates of $PM_{2.5}$ emissions; the districts are not homogeneous; monitor concentrations are not necessarily representative of the entire district; and the sample size and diversity of sites are limited.

Acknowledgement

We thank the Chinese Meteorological Data Net and Fire Information for Resource Management System for providing the daily meteorological data and the burning point distribution information of Jilin Province.

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