The Impact of Meteorological Factors on Fine Particulate Pollution in Northeast China

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ABSTRACT

Due to biomass burning and coal combustion, heavy fine particulate matter (PM_{2.5}) pollution frequently occurs in Northeast China, threatening the health of more than 117 million inhabitants. Although meteorological conditions have always been considered key factors in the accumulation and dilution of PM_{2.5} pollution, their exact contribution to particulate pollution in Northeast China is still highly uncertain. Applying multiple regression analysis to observational data, we identify the wind speed, temperature inversion, and height of the planetary boundary layer as the dominant meteorological factors affecting PM_{2.5} pollution (PM_{2.5} > 75 µg m⁻³) in the major cities of Northeast China, with the wind speed and the planetary boundary layer playing the primary roles in Harbin and Shenyang, and Changchun, respectively. Heavy pollution (PM_{2.5} > 150 µg m⁻³) in this region typically occurs when the wind speed is less than 20 knots, the planetary boundary layer is below 500 m, and the temperature inversion is greater than 6°C. These results suggest that reducing the PM_{2.5} pollution requires us to focus not only on anthropogenic emissions but also on special meteorological conditions that can affect the air pollution mechanisms in Northeast China.

Keywords: Fine particulate (PM_{2.5}) pollution; Multiple regression method; Wind speed; Temperature inversion; Planetary boundary layer height.

INTRODUCTION

Several extremely severe atmospheric haze events have occurred recently in Northeast China, a major crop straw burning region of China, with air pollution reaching up to nearly 2–3 times of the historical record (Chen *et al.*, 2015; Wen *et al.*, 2018). Fine particulate matter (PM_{2.5}) has been proved harmful to human health and regarded as the main factor impairing visibility (He *et al.*, 2001; Wang and Christopher, 2003; Jung *et al.*, 2010; Heal *et al.*, 2012; Kan *et al.*, 2012). It exerts large influences on the development of planetary boundary layer (PBL) through the positive feedback loop between aerosol and PBL (Petäjä *et al.*, 2016; Li *et al.*, 2017b; Lou *et al.*, 2019) which in turn deteriorates the air quality. Besides, aerosol tends to affect the formation

and development of cloud and precipitation through directly altering the radiation reaching the ground surface (Lohmann and Feichter, 2001; Yang *et al.*, 2016) or indirectly altering the structure of clouds by acting as cloud condensation nucleus (Twomey, 1977; Chen *et al.*, 2016; Guo *et al.*, 2016; Guo *et al.*, 2019), albeit its inconclusive effect on weather and climate systems (Rosenfeld *et al.*, 2014; Fan *et al.*, 2016; Li *et al.*, 2019). In view of its potential huge influence, fine particulate pollution has attracted great attention from the Chinese government. Many regulations and standards have been made to control the fine particulate pollution (Wen *et al.*, 2018). By adopting these measures, a gradual decrease in the PM_{2.5} concentration over time has been witnessed recently (Wen *et al.*, 2018). However, PM_{2.5} pollution in Northeast China is still non-negligible, especially around harvest time (Chen *et al.*, 2017).

The pollution during the heating season in Northeast China is mainly caused by evening biomass burning and coal combustion (Fang *et al.*, 2001; Zhang *et al.*, 2011; Fang *et al.*, 2017). In addition, meteorological factors are important to the variation of PM_{2.5} concentrations. Researches show

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that wind speed has a negative effect on PM_{2.5} concentration (Chen *et al.*, 2015; Liang *et al.*, 2015; Chen *et al.*, 2017; Wen *et al.*, 2018). Wind speed can facilitate plume spread and dilution, leading to lower PM_{2.5} concentrations. In such way, atmospheric horizontal mixing has been considered as one of the most efficient dilution mechanisms (Marcazzan *et al.*, 2001). Studies show that lower height of the planetary boundary layer (HPBL) weakens the dispersion ability of the atmosphere (Seinfeld *et al.*, 1998; Dickerson *et al.*, 2007; Marcazzan *et al.*, 2001; Zhang *et al.*, 2015; Wen *et al.*, 2018). HPBL, also known as the *boundary layer top*, refers to the thickness of the planetary boundary layer. The characteristic of the boundary layer height is that the turbulence coefficient at this height is zero and the free atmosphere is above it. The diffusion and transportation of pollutants in the lower atmosphere depends to a large extent on the boundary layer structure. Within the boundary layer, turbulence can fully mix particles and gases (Garratt, 1994). In addition, the inversion layer boosts the accumulation of pollutants in the atmosphere (Wang *et al.*, 2014b; Fang *et al.*, 2017). Temperature inversion is a reversal of the normal behavior of temperature in the troposphere, in which a layer of cool air at the surface is overlain by a layer of warmer air. When inversion occurs, upward movement of the lower atmosphere decreases and the pollutants are trapped in the lower atmosphere (Xu *et al.*, 2019). In winter, the recurrent or continuous thermal inversions with fog at ground level are the major contributors to the massive amount of air pollutants accumulated in the lower layer of the atmosphere (Marcazzan *et al.*, 2001). Moreover, haze weather can form in a faster way under high humidity conditions. Some researchers conclude that the relative humidity (RH) could well explain the daily variations of PM_{2.5} (Sun *et al.*, 2013; Fang *et al.*, 2017; Ma *et al.*, 2017). Previous studies indicated that the synoptic scale meteorological conditions and multiple meteorological factors can have a complicated impact to the PM_{2.5} pollution (Chen *et al.*, 2018; Liu *et al.*, 2018; Miao *et al.*, 2017; Wang *et al.*, 2014a).

Three typical large cities of Northeast China (i.e., Harbin, Changchun, and Shenyang) were studied in this research, using statistical data and regression model analysis, to investigate the impact of different meteorological factors on major cities in Northeast China. The study result of this research is of great benefit to making suitable and effective strategies for PM_{2.5} control in Northeast China.

DATA AND METHODS

Study Area

As shown in Fig. 1, Northeast China is covered mostly by plain. The Northeast Plain is surrounded by mountains, alluvial plains and terraces, with an elevation of about 200 m. The Northeast Plain is located in a temperate and warm temperate zone with continental monsoon climate characteristics. Significant seasonal differences exist in this area. The summer is short, warm and rainy. Meanwhile the winter is long, cold, and snowy. And the monsoon alternates between winter and summer.

Considering their meteorological conditions and urban development status, three typical large cities in Northeast

China were selected in this study to reflect the major characteristics of PM_{2.5} pollution in Northeast China. Among the three cities, Harbin, the capital of Heilongjiang Province, is located in the highest latitude area, having the lowest temperature, with a flat terrain. Over 10.9 million people live in Harbin. The southeastern part of Harbin is located in the hills; meanwhile, mountainous area occupied the north part. The Songhua River flows through the middle part of Harbin. Changchun is located in the middle part of Northeast China with over 7.5 million people. The Changchun area, apart from a small area of low hills in the east, is mostly comprised of terraces. The terrain of Changchun is flat and convenient for transportation (Fang *et al.*, 2001). In Changchun, from November to March, coal burning phenomenon for heating purpose is widespread. The heating area is scattered in one-fourth of the city area (Fang *et al.*, 2001). Shenyang, the largest city in Northeast China, has over 8.3 million people (Xu *et al.*, 2000; Han *et al.*, 2010). It is located in the southeastern part of Northeast China, mainly in the plains, with mountains and hills concentrated in the southeast. Shenyang shows similar meteorological characteristics with the other two cities mentioned above: a monsoon-influenced humid continental climate, which has monsoon-caused hot, humid summers and dry, cold winters driven by the Siberian anticyclone (Han *et al.*, 2010).

Data Source and Treatment

The time period of the studied PM_{2.5} data ranges from 2015 to 2017, provided by the China Meteorological Administration. The continuous hourly PM_{2.5} concentration data has been monitored by the 33 stations: 12 sites in Harbin, 10 sites in Changchun, and 11 sites in Shenyang. As can be seen in Fig. 1, the sites are evenly distributed throughout the cities. Thus the hourly average value of these sites can reasonably represent the PM_{2.5} concentration of the three cities. To keep consistency with the meteorological data, the PM_{2.5} concentration was calculated at 08:00 and 20:00 local time. The PM_{2.5} data is classified into three states: the non-pollution state (PM_{2.5} ≤ 75 µg m⁻³), pollution state (PM_{2.5} > 75 µg m⁻³), and heavy pollution state (PM_{2.5} > 150 µg m⁻³) (Ma *et al.*, 2017; Tian *et al.*, 2017).

Meteorological data comes from the radiosonde measurements provided by the Integrated Global Radiosonde Archive developed by the American National Climatic Data Center (NCDC) (Durre *et al.*, 2006). The humidity data and wind data are extracted specifically with wind velocity and wind direction at 850 hPa. In general, temperature drops as the altitude increases, beneficial to the convective phenomenon which accelerates the pollutants in the lower layer moving and diffusing upward. However, when temperature inversion occurs, the upward movement of the lower atmosphere is weakened, causing the accumulation of atmospheric pollutants in the lower layer. Temperature inversion phenomenon can be detected by the temperature profile of the atmosphere. Two factors, namely the temperature difference of the inversion layer (*TI_T*) and the depth of the inversion layer (*TI_D*), are used to describe the intensity of temperature inversion. In this research, the two factors of the inversion layer are derived from the Integrated Global Radiosonde

Fig. 1. Map of the study area: (a) the topographic map of China and the location of Northeast China; (b) the topographic map of Northeast China and the location of Shenyang, Changchun, and Harbin; and the location of PM_{2.5} studying sites in (c) Shenyang, (d) Changchun, and (e) Harbin.

Archive (IGRA) soundings data. We first analyze the temperature data for different air layers and find if there exists a temperature sequence segmentation in the profile that has monotonic increasing trend with the increase of the layer heights. If exist, the temperature inversion is defined. Then the temperature difference is calculated by subtracting the temperatures at the top and bottom of the inversion layers. And the depth of the inversion layer is calculated by subtracting the heights at the top and bottom of the inversion layers.

HPBL data used in this research is provided by National Centers for Environmental Prediction (NCEP) and Final (FNL) Reanalysis data. It is collected at 06:00 and 18:00 UTC. The HPBL data is a grid dataset and the horizontal resolution of HPBL is $1 \times 1^\circ$ (Zang *et al.*, 2017). In this research, the HPBL values of Harbin, Changchun and Shenyang are calculated using the inverse distance weighting method based on the values in four closest grid points.

Methods

In order to decouple the contribution of different meteorological factors, a multiple regression model was used

to analyze the correlations between PM_{2.5} concentration and meteorological factors. Based on atmospheric dispersion equations, the particulate concentration is correlated with meteorological parameters in multiplicative form other than additive form (Hien *et al.*, 2002; Chaloulakou *et al.*, 2003; Gu *et al.*, 2018). The multiple regression analysis model can be constructed as follows:

$$B = k \times f(\tau_n) \quad (1)$$

where B represents the monitored PM_{2.5} concentration, k represents autochthonic contribution to PM_{2.5}. k is considered to remain unchanged during each season. $f(\tau_n)$ represents the meteorological impact on PM_{2.5}. Furthermore, the regression model can be expressed as follows:

$$B = k \prod (P_i)^{\alpha_i} \quad (2)$$

The exponent α_i represents the response of particulate concentration B to the rate of change in meteorological

parameter P_i . $f(\tau_n)$ was calculated using five meteorological factors (P_i) in this model: wind velocity (WV), HPBL, TI_T , TI_D and RH. As a result, the model can be expressed as follows:

$$B = k \times (WV)^{\alpha_1} \times (HPBL)^{\alpha_2} \times (TI_T)^{\alpha_3} \times (TI_D)^{\alpha_4} \times (RH)^{\alpha_5} \quad (3)$$

Then, take the logarithm for both sides of this equation. Eq. (3) can be further transformed to a multiple linear regression model:

$$\ln B = \ln k + \sum \alpha_i \ln(P_i) + \varepsilon \quad (4)$$

where $\ln k$, α_i and ε represent the intercept, regression coefficients, and the error term respectively. WV, RH, TI_T , TI_D , and HPBL were selected in this research as the studied meteorological parameters which influence the $PM_{2.5}$ concentration characteristics in Northeast China. To find the determinant(s) of the $PM_{2.5}$ concentrations among various indicators, the data were analyzed by a stepwise multiple regression method with a significance level of 95% ($p = 0.05$) set for the regression coefficients.

The regression coefficient α_i can only represent the positive or negative relationship between the $PM_{2.5}$ concentration and the meteorological factors. To find the most important factors that impact the $PM_{2.5}$ concentration in different cities of Northeast China, we calculated the standardized coefficient of the regression model. The standardized coefficient can compare the relative importance of different kind of factors

to the $PM_{2.5}$ concentration. The bigger the absolute value is, the more important the meteorological factor will be (Newman and Browner, 1991).

RESULT AND DISCUSSION

Variation of the $PM_{2.5}$ Concentrations Correlated with Different Meteorological Factors

Massive biomass burning and coal consumption together with meteorological conditions potentially cause the high level of $PM_{2.5}$ pollution in Northeast China's winter (Han et al., 2010; Segura et al., 2013). Studies show that $PM_{2.5}$ pollution in Northeast China originates from anthropogenic activities, such as straw burning and coal combustion for both industrial and domestic purpose (Zhang et al., 2010; Guan et al., 2018). Meanwhile, individual meteorological factors such as relative humidity, wind speed and temperature inversion have non-negligible impacts on local $PM_{2.5}$ concentrations (Cheng and Lam, 1998; Ruellan and Cachier, 2001; Wen et al., 2018). The distribution and variation of the source of pollution are usually stable during each season. However, the dilution and accumulation abilities impacted by the meteorological conditions can change significantly. Investigating the impacts of meteorological factors is beneficial to a better understanding of the variations of $PM_{2.5}$ mass concentrations.

As shown in Fig. 2, the correlation between $PM_{2.5}$ concentration, and wind direction and speed were similar in the three cities. $PM_{2.5}$ concentration is negatively associated with wind speed (Chen et al., 2017; Wen et al., 2018). High $PM_{2.5}$ concentration tends to appear in a low wind speed

Fig. 2. Relationships between atmospheric pollutant concentrations, wind direction, and wind speed in (a) Harbin, (b) Changchun, and (c) Shenyang. Direction frequency and average $PM_{2.5}$ concentrations in different direction during pollution days in (d) Harbin, (e) Changchun, and (f) Shenyang.

situation. In Harbin, Changchun, and Shenyang, 79.2%, 79.1%, and 80.4% of the heavy $PM_{2.5}$ pollution occurs in the days when the wind speed is less than 20 knots (a *knot* is a unit typically used to indicate wind speed, and thus used in this research; 1 knot = 1.852 km h^{-1}). Biomass burning in spring and autumn and coal combustion for domestic heating in winter produce a great deal of air pollutants (Zhang *et al.*, 2010; Bao *et al.*, 2015). Higher wind speed is likely to promote the spread of pollutant, which is beneficial for the dilution of $PM_{2.5}$ pollutants (Wen *et al.*, 2018). The westerly wind prevails during pollution days in Northeast China. In Harbin, over 70% of pollution days ($PM_{2.5} > 75 \mu\text{g m}^{-3}$) are related with the wind which has a direction between $240\text{--}330^\circ$. As for Changchun and Shenyang, the dominant wind direction in pollution days is concentrated at $210\text{--}330^\circ$. In general, Harbin, Changchun, and Shenyang are mainly dominated by the southwest wind during the whole year; meanwhile the northwest wind is the prevailing wind in winter.

As shown in Fig. 3, in terms of statistics, there is a general negative correlation between HPBL and $PM_{2.5}$ concentrations for Harbin, Changchun, and Shenyang. Heavy $PM_{2.5}$ pollution usually occurs in the lower HPBL ($< 500 \text{ m}$). HPBL plays a vital role in the variation of $PM_{2.5}$ concentration. The barrier effect at the top of the planetary boundary layer hinders air pollutants from being transported to the free troposphere, so that aerosol particles are constrained in the PBL (You *et al.*, 2015; Li *et al.*, 2017a;). Lower HPBL is usually related with higher concentrations of $PM_{2.5}$, and higher HPBL is usually associated with smaller ground level $PM_{2.5}$ concentration as a result of large vertical mixing ability (Yao *et al.*, 2012).

As can be seen in Fig. 4, $PM_{2.5}$ concentration is significantly and positively correlated with the intensity of temperature inversion which is described by TI_T and TI_D . In Harbin, Changchun, and Shenyang, 60.6%, 44.8%, and 56.9% of $PM_{2.5}$ pollution days occur with temperature inversion phenomenon, respectively. Only 14.4%, 18.4%, and 15.4% of $PM_{2.5}$ pollution days have no temperature inversion. $PM_{2.5}$ concentration rises significantly when TI_T is greater than 6°C in Harbin and Changchun. However, the relationship

between TI_T and $PM_{2.5}$ in Shenyang is not so significant in pollution days. The TI_D in Shenyang is generally thicker than that of other two cities. Heavy pollution usually occurs when TI_D is bigger than 600 m in Harbin and Shenyang. Compared to summer, the inversion layer in winter is thicker and has a longer duration. The atmosphere remains static once temperature inversion occurs. In static atmosphere, air pollutants are not easily dispersed vertically and, thus, accumulated near the surface. Additionally, a large temperature difference within a thin inversion layer can also cause high concentrations of $PM_{2.5}$ in the ground layer.

As can be seen in Fig. 5, the relationship between RH and $PM_{2.5}$ in Northeast China is not as significant as other air pollution areas. There is even a negative correlation between $PM_{2.5}$ and RH. Possible reasons are that rainy and snowy weather accompanied with moist air can deposit the particulate pollutants so that air becomes clear, and when the air pollution is caused by the dust particles, the moisture in the air remains constantly low (Sun *et al.*, 2013).

Quantitative Multiple Regression Analysis between $PM_{2.5}$ Concentration and Meteorological Factors

$PM_{2.5}$ concentration has dropped continuously during the past three years in Northeast China. However, daily $PM_{2.5}$ levels varied remarkably, rising and falling rapidly with alternating sharp peaks and deep troughs (Wen *et al.*, 2018). In Table 1, the confidence coefficient for meteorological factors above 95% confidence level ($p\text{-value} < 0.05$) indicates the factors significantly impact the daily variation of $PM_{2.5}$ concentration to some extent. Wind speed, HPBL, and temperature inversion are important meteorological factors affecting the $PM_{2.5}$ pollution in Northeast China. During pollution days, the regression coefficients of wind speed and HPBL are negative values, which show a clear negative influence of wind speed and HPBL on fine particle concentrations. Meanwhile, the values for the coefficients of TI_T and TI_D are positive, which indicates that temperature inversion has a positive impact on the accumulation of $PM_{2.5}$. A meteorological factor plays the dominant role in affecting $PM_{2.5}$ pollution when its standardized coefficient

Fig. 3. Correlation between $PM_{2.5}$ and the height of the planetary boundary layer in Harbin, Changchun, and Shenyang for (a) pollution days ($> 75 \mu\text{g m}^{-3}$) and (b) non-pollution days ($\leq 75 \mu\text{g m}^{-3}$).

Fig. 4. Statistics of PM_{2.5} concentrations with temperature inversion. Variation of the PM_{2.5} concentrations correlated with the temperature difference of the inversion layer (TI_T) during (a) pollution days ($> 75 \mu\text{g m}^{-3}$) and (b) non-pollution days ($\leq 75 \mu\text{g m}^{-3}$). Variation of the PM_{2.5} concentrations correlated with the depth of temperature inversion (TI_D) during (c) pollution days ($> 75 \mu\text{g m}^{-3}$) and (d) non-pollution days ($\leq 75 \mu\text{g m}^{-3}$).

has the biggest absolute value. By comparing the standardized coefficients of different factors in the regression model, the most important factors are concluded. Wind speed is the key meteorological factor impacting PM_{2.5} concentrations in Harbin and Shenyang. Meanwhile, HPBL is the key factor in Changchun.

Straw burning and pollutant emission, near-surface temperature inversion, and static wind together with other extreme meteorological conditions contribute to the PM_{2.5} pollution, especially in autumn and winter. The breeze hinders the dispersion and transport of the atmospheric pollutants released by straw burning. On the contrary, high wind speed is beneficial to the horizontal dilution of the pollutants. On the other hand, the turbulence is strengthened with the increase of wind speed, which is also beneficial to the pollutant dilution and spreading. There are significant differences between the situations with and without the existence of temperature inversion. Temperature inversion decreases the upward movement of the lower atmosphere and causes the pollutants trapped in the lower atmosphere. Frequent atmospheric conditions with temperature inversion

in winter can cause the accumulation of atmospheric particles (He *et al.*, 2001; Han *et al.*, 2010). The convection between upper and lower layers decreases, so that the atmospheric pollutants in the near-surface layer can hardly be transported upward. At the same time, the pollutants never stop accumulating, which exacerbates air pollution. The diffusion and transportation of pollutants in the lower atmosphere depends to a large extent on the boundary layer structure. Within the boundary layer, turbulence can fully mix particles and gases. All the three factors have significant influence on the PM_{2.5} concentrations in Northeast China. As can be seen in the multiple regression result (Table 1), during pollution days, all the three cities have the wind speed as one of the major impact factors. However, different from other two cities, the temperature inversion is not a major impact factor for Changchun. Such result may be caused by the fact that the altitude of Changchun (236.8 m) is higher than Harbin (171.7 m) and Shenyang (41.6 m). And the temperature inversion has the characteristic that it occurs more obviously in the lowland (or valley) area than the highland area.

As can be seen from Table 2, during non-pollution days,

Fig. 5. Variation of the $PM_{2.5}$ concentrations correlated with different RH condition during (a) pollution days ($> 75 \mu g m^{-3}$) and (b) non-pollution days ($\leq 75 \mu g m^{-3}$) in Harbin, Changchun, and Shenyang respectively. The RH is divided into 5 segments (i.e., 0–20, 20–40, 40–60, 60–80, and 80–100).

Table 1. Regression coefficients, standardized coefficients and p-values of different meteorological factors during pollution days in Northeast China.

City	Evaluating index	Wind speed	HPBL	TI_T	TI_D	RH
Harbin	Regression coefficient	−0.237	−0.084	0.110	0.026	−0.042
	Standardized coefficient	−0.252	−0.226	0.236	0.006	−0.052
	p-value	8.03E-07	2.11E-05	1.27E-06	0.938	0.279
Changchun	Regression coefficient	−0.146	−0.061	−0.023	0.277	−0.034
	Standardized coefficient	−0.189	−0.194	−0.037	0.024	−0.071
	p-value	0.024	0.022	0.556	0.617	0.503
Shenyang	Regression coefficient	−0.141	−0.028	0.010	1.482	0.043
	Standardized coefficient	−0.247	−0.120	0.029	0.214	0.107
	p-value	6.96E-05	0.06437	0.652	0.001	0.088

Table 2. Regression coefficients, standardized coefficients and p-values of meteorological factors during clear days in Northeast China.

City	Evaluating index	Wind speed	HPBL	TI_T	TI_D	RH
Harbin	Regression coefficient	0.103	−0.098	0.082	0.294	0.025
	Standardized coefficient	0.084	−0.243	0.189	0.053	0.035
	p-value	0.196	0.0002	0.004	0.399	0.591
Changchun	Regression coefficient	0.059	−0.065	0.068	1.601	−0.134
	Standardized coefficient	0.063	−0.175	0.126	0.315	−0.157
	p-value	0.365	0.012	0.064	2.67E-05	0.030
Shenyang	Regression coefficient	0.080	0.031	0.048	1.461	0.003
	Standardized coefficient	0.120	0.117	0.124	0.236	0.005
	p-value	0.092	0.103	0.126	0.001	0.942

HPBL and temperature inversion are important factors affecting $PM_{2.5}$ in Harbin and Changchun. In Shenyang, TI_D is the only important determinant impacting $PM_{2.5}$ concentration. In summer, the thickened mixing layer improves the dispersion of pollutants in the atmosphere. In winter, frequent and persistent thermal inversions at ground level drive considerable amount of air pollutants to accumulate in the lower layer of the atmosphere (Marcazzan *et al.*, 2001). Although wind speed, HPBL, and TI_T are important factors of $PM_{2.5}$ concentration, their correlations with $PM_{2.5}$

concentration during non-pollution days are not significant.

Fig. 6 shows the occurrence of $PM_{2.5}$ pollution and non-pollution days in different meteorological conditions from 2015 to 2017. The meteorological factors for different cities are selected based on the significance level of 95% in Table 1. For Harbin, HPBL, WV, and TI_T are major impact factors. $PM_{2.5}$ pollution usually occurs, with a possibility of 91.6%, when the wind speed is under 20 knots, HPBL is lower than 1500 m and TI_T is higher than 8°C. On the contrary, the possibility of occurrence of $PM_{2.5}$ pollution is

Fig. 6. The occurrence of PM_{2.5} pollution and non-pollution days in different meteorological conditions from 2015 to 2017 in (a) Harbin, (b) Changchun, and (c) Shenyang.

only 27.2% for the whole year. For Changchun, PM_{2.5} pollution is majorly impacted by wind speed and HPBL, the possibility is 61.7% when the wind speed is under 20 knots and HPBL is lower than 600 m. Meanwhile, the possibility is only 22.7% for the whole year. As for Shenyang, the possibility of the occurrence of PM_{2.5} pollution rises from 24.9% to 70.3% when the wind speed is under 20 knots, and TI_D is greater than 775 m.

CONCLUSIONS

To evaluate the effect of meteorological conditions on PM_{2.5} pollution in Northeast China, we applied a regression method to long-term ground-based PM_{2.5} data and radiosonde measurements. We found that the wind speed, HPBL, and temperature inversion were the primary factors influencing the fine particulate pollution in this region. Whereas the wind speed exhibited the strongest correlations with the PM_{2.5} levels in Harbin and Shenyang, the HPBL played the key role in Changchun, with the meteorological data showing significant negative effects from both of these factors on the fine particle concentration. By contrast, the temperature inversion, described using TI_T and TI_D, was positively correlated with the concentration.

In Harbin, the probability of PM_{2.5} pollution was 91.6% when the wind speed was less than 20 knots, the HPBL was below 1500 m, and TI_T was greater than 8°C. In Changchun, the probability was 61.7% when the wind speed was less than 20 knots and the HPBL was below 600 m. Finally, in Shenyang, the probability was 70.3% when the wind speed

was less than 20 knots and TI_D was more than 775 m. Unlike other typical polluted areas, the variation in the PM_{2.5} concentration during polluted days in Northeast China little depended on the RH.

In addition to anthropogenic emissions, which necessitate local control strategies, the ambient meteorological conditions play a large role in PM_{2.5} pollution in Northeast China and must be considered in order to efficiently decrease air pollution in this region. For example, when temperature inversion occurs, reducing coal and petroleum consumption should be contemplated as a potential preventative measure.

Our study provides preliminary results on the major meteorological factors that affect the accumulation and dispersion of PM_{2.5} pollution. Further studies may examine additional meteorological parameters and expand the observation period. Furthermore, we used the nocturnal HPBL data which is usually dominated by the residual layer, and the relevancy between PM_{2.5} and HPBL may not be true in nighttime. This issue can also be addressed in the future.

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