The Effect of Meteorological Factors, Seasonal Factors and Air Pollutions on the Formation of Particulate Matter

Cai Chen, Wei Li *, Leilei Dong and Xiyuan Li

Biomedical Engineering Institute, School of Control Science and Engineering, Shandong University, Jinan 250061, China

*Corresponding author e-mail: cindy@sdu.edu.cn

Abstract. To investigate the effect of meteorological factors, seasonal factors and Air Pollutions on the formation of particulate matter (PM2.5) in Jinan, China. Nonlinear dynamic inversion model was established to analyze the effect of meteorological factors, seasonal factors and CO, PM10, SO2, NO2, O3 on PM2.5 formations in different seasons. Temperature has a great influence on PM2.5 concentration variation. Precipitation exacerbate the formation of PM2.5 in Winter. Wind speed make a little contribution to PM2.5 formation in Jinan during different season. The formation of PM2.5 was influenced by confounding factors.

Keywords: Ambient pollutants, particulate matter, nonlinear dynamic inversion model, meteorological factor.

1. Introduction

With the gradually increasing improvement of public health awareness, haze has been paid more attentions, which is caused mainly by particulate matter (PM2.5) [1, 2]. A number of statistics studies have shown that long-term exposure to PM2.5 has a passive effect on people’s health [3-5]. It’s much significant to figure out the reason of the formation of PM2.5. In China, the ambient PM2.5 has become one of the most serious environmental problems. Since 2012, the concentration of PM2.5 has been monitored and started to report for public. Jinan is the economic, cultural, transportation and political center of Shandong Province, China. However, people in Jinan have been experienced serious PM2.5 pollution [6-8]. The PM2.5 concentrations in 2017 in Jinan varied from 7μg/m³ to 276μg/m³ with an average of 64μg/m³, which exceeds the annual average PM2.5 concentration limit value. The formation of PM2.5 involves a series of photochemical reaction [9, 10], while its specific formation mechanism has been not explicit.

To date, previous studies have demonstrated the link between PM2.5 and meteorological condition, other air pollution and season. Liu J et al. discovered a phenomenon of the time-lagged intercity correlations of PM2.5 time series between different cities, which related to meteorological variation [11]. It has been conclusively shown that the concentration of PM2.5 followed the periodic U-shaped variation pattern from January to December [12]. Zhong Q et al. found that the characteristics of the effect of meteorological factor on PM2.5 fluctuation obeyed the probabilistic functions [13]. In addition, some researches on PM2.5 have focused on modeling to analyze its formation using meteorological factors and air pollution. For example, Yang, K et al. found the source of organophosphate esters in PM2.5 according
to the hybrid single particle lagrangian integrated trajectory model and wind direction frequency data [14]. Zawacki M et al. evaluated the contribution of mobile air pollution source to PM$_{2.5}$, using the comprehensive air quality model with extensions model [15]. However, the application of model to study the relationship between PM$_{2.5}$ and its influence factor, mainly focused on their linear relationship rather than nonlinear relationship which the formation of PM$_{2.5}$ is caused by a combination of factors. So far, few published studies have been conducted to determine the comprehensive effects of meteorological factor, air pollution and seasonal factor.

The purpose of this study was to investigate the complicated impact of meteorological factors, other air pollution and seasonal factors on the formation of PM$_{2.5}$ based on nonlinear dynamic inversion model in Jinan, China. The results of this research will be helpful for further research on the process and mechanism of PM$_{2.5}$ concentration changes affected by multiple factors, hopefully provide the impetus and scientific basis for relevant policy-making, and also enhance the public awareness of the environmental protection.

2. Data and method

2.1. Data Source

The air pollution data in Jinan from March 2014 to February 2018 concluding particulate matter (PM$_{2.5}$), inhalable particles (PM$_{10}$), sulfur dioxide (SO$_2$), nitrogen dioxide (NO$_2$) for 24-hour, carbon monoxide (CO) and Ozone (O$_3$) for 8-hour, was obtained from Jinan Environment Monitoring Center. The daily average temperature (T), daily atmospheric pressure at sea level (SLP), daily average relative humidity (H), daily total precipitation (PP), and daily average wind speed (V) at the same period was from the Jinan Bureau of Meteorology. Furthermore, 12 months were stratified into four seasons, Spring (March, April and May), Summer (June, July and August), Autumn (September, October and November) and Winter (December, January and February).

2.2. Method

Nonlinear dynamic inversion model has been used in the past to investigate local climate based on observational data [16, 17]. In this paper, it was applied to analyze the driving force for the formation of PM$_{2.5}$.

The dynamic equation is as follows:

$$\frac{dX_j(t)}{dt} = f_j(t, X_1(t), X_2(t), \ldots , X_n(t)), \ j = 1, 2, \ldots , n$$

(1)

Where $X_j(t)$ is the state variable of the nonlinear system, is the number of state variable. $f_j(t, X_1(t), X_2(t), \ldots , X_n(t))$ is the general nonlinear function of $X_1(t), X_2(t), \ldots , X_n(t)$. $X_1(t), X_2(t), \ldots , X_n(t)$ is the series of observational data we have obtained. Actually, the concrete form of equation (1) is not known to us, but the observational data series $X_1(t_1), X_2(t_1), \ldots , X_n(t_1), X_1(t_2), X_2(t_2), \ldots , X_n(t_2), \ldots , X_1(t_m), X_2(t_m), \ldots , X_n(t_m)$ are served as $m$ solutions of equation (1).

Equation (1) can be approximatively written as equation (2) and $f_j(t, X_1(t), X_2(t), \ldots , X_n(t))$ can be expressed as equation (3).

$$\frac{X_j(t_i) - X_j(t_{i-1})}{t_i - t_{i-1}} = f_j(t, X_1(t), X_2(t), \ldots , X_n(t)), \ j = 1, 2, \ldots , n, i = 2, 3, \ldots , m$$

(2)
\[ f_j(t, X_1(t), X_2(t), \ldots, X_n(t)) = \sum_{k=1}^{m} b_k Q_k, k = 1, 2, \ldots, m \]  \tag{3}

Where \( b_k \) is the coefficient of \( Q_k \). Equation (2) is expressed as

\[ D = Qb \]  \tag{4}

In which,

\[
\begin{bmatrix}
Q_1 \\
Q_2 \\
\vdots \\
Q_n
\end{bmatrix} = 
\begin{bmatrix}
Q_{11} & Q_{12} & \cdots & Q_{1k} \\
Q_{21} & Q_{22} & \cdots & Q_{2k} \\
\vdots & \vdots & \ddots & \vdots \\
Q_{m1} & Q_{m2} & \cdots & Q_{mk}
\end{bmatrix}
\] \hspace{1cm}

\[
\begin{bmatrix}
d_1 \\
d_2 \\
\vdots \\
d_n
\end{bmatrix} = 
\begin{bmatrix}
X_j(t_2) - X_j(t_1) \\
t_2 - t_1 \\
X_j(t_3) - X_j(t_2) \\
\vdots \\
X_j(t_m) - X_j(t_{m-1}) \\
t_m - t_{m-1}
\end{bmatrix}
\]

In equation (4), \( b \) can be calculated. In this paper, \( D \) represents the following day's concentration of PM2.5 and \( Q \) represents the observational series concluding PM10, SO2, NO2, O3, T, SLP, H, PP and V. Contribution rate was calculated according to equation (5).

\[ S_k = \frac{b_k^2}{\sum b_k^2}, k = 1, 2, \ldots, m \]  \tag{5}

3. Results

The daily average concentration of PM2.5, PM10, SO2, NO2, O3 and CO was 74μg/m³, 139μg/m³, 40μg/m³, 48μg/m³, 64μg/m³ and 1190μg/m³, respectively.

Rate of Contribution to the PM2.5 formations in Spring was presented in Fig 1. It can be found that PM2.5*PP was the primary factor in 2014 Spring and 2016 Spring, its contribution rate was 40.8% and 38.9%, respectively. In 2015 Spring, NO2*T could account for 14.6% factor for PM2.5 formations. While during 2017 Spring, CO*PP was the first driving force for the PM2.5 formations, whose contribution rate was 13.0%.

Fig 2 illustrates the proportion of the driving forces with their contribution rate to PM2.5 formations in Winter. O3*PM10 contribution rate in 2016 Winter and 2017 Winter were 3.8% and 4.7%, respectively. T*PP contribution rate in 2014 Winter and 2015 Winter were 20.4% and 7.9%, respectively. In 2014 Winter, 2016 Winter and 2017 Winter, PM2.5*CO contribution rate were 6.7%, 15.2% and 13.0%, respectively. Furthermore, CO *PP contribution rate in 2014 Winter, 2015 Winter and 2016 Winter were 16.3%, 49.9% and 12.9%, respectively.
Table 1. Daily ambient pollutant concentration and meteorological conditions

| Variable             | X ± S | Min | P25 | P50 | P75 | Max |
|----------------------|------|-----|-----|-----|-----|-----|
| **Pollutions(μg/m³)**|      |     |     |     |     |     |
| PM$_{2.5}$           | 74 ± 50 | 7   | 41  | 61  | 92  | 631 |
| SO$_2$               | 40 ± 33 | 5   | 20  | 30  | 46  | 333 |
| CO                   | 1190 ± 590 | 360 | 820 | 1060 | 1400 | 5940 |
| O$_3$                | 64 ± 39 | 4   | 35  | 57  | 89  | 204 |
| NO$_2$               | 48 ± 19 | 15  | 34  | 45  | 59  | 156 |
| PM$_{10}$            | 139 ± 74 | 14  | 89  | 125 | 172 | 824 |
| **Meteorology**      |      |     |     |     |     |     |
| Temperature (℃)      | 15 ± 10 | -13 | 6   | 17  | 24  | 34  |
| Humidity (%)         | 54 ± 20 | 15  | 38  | 52  | 69  | 100 |
| Pressure (hPa)       | 1017 ± 47 | 998 | 1009 | 1017 | 1025 | 1044 |
| Wind Speed (Km/h)    | 9 ± 3 | 2   | 6   | 8   | 10  | 26  |
| Precipitation (mm)   | 2 ± 8 | 0   | 0   | 0   | 0   | 127 |

Note: X, mean value; S, standard deviation; Min, minimum; Max, maximum; P25, P50, P75, Quartiles

Figure 1. Rate of contribute to PM2.5 formation in Jinan Spring from 2014 to 2017
4. Discussion

More evidences have indicated that PM2.5 is positively correlated with the incidence and mortality of respiratory diseases, cardiovascular diseases, cancer and other diseases [3, 18, 19]. The formation of PM2.5 and its concentration variation involve a series of complex chemical reactions and physical changes [20], but its specific mechanism has been not clear. The paper was designed to research the effect of meteorological factors, ambient pollution (SO$_2$, NO$_2$, CO, O$_3$, PM10, PM2.5) and seasonal factor on the PM2.5 formation. In this paper, nonlinear dynamic inversion model was utilized to quantitatively analyze the contribution rate of driving force to PM2.5 concentration change. The results showed that PM2.5 concentration variation was synthetically affected by meteorological factors, air pollution (SO$_2$, NO$_2$, CO, O$_3$, PM10, PM2.5) and season. The sum of CO contribution rate was 24.7% in 2017 Spring, 26.0% in 2016 Spring, respectively. The sum of CO contribution rate was 31.4% in 2017 Winter, 36.1% in 2016 Winter, 60.6% in 2015 Winter and 25.1% in 2014 Winter, respectively, which indicates that CO was the main factors affecting PM2.5 formation as a consequence that there was a much lower temperature in Jinan, coal combustion is essential for heating[21-23].

In 2015 Spring, temperature was the primary driving force for PM2.5 formations, total contribution rate reaching to 25.2%. Average temperature in 2015 Spring was much lower than the other years of Spring (18.0°C in 2014 Spring, 15.9°C in 2015 Spring, 17.1°C in 2016 Spring, 17.0°C in 2017 Spring). It could be accounted for that low temperature contributes to more fossil fuel consumption for heating, which produced more fine particulate matter. Moreover, researches showed that coexistence low temperature and PM2.5 could increase the risk of illness [22]. Thus, susceptible population, such older people and young children, should pay more attention to coexistence low temperature and high concentration PM2.5. In 2014 Spring and 2016 Spring, driving force, PM2.5*PP, PP*PM10, T*PP and
SO$_2$PP, whose total contribution rate were more than 2%, emerged when there is less precipitation (0.86mm in 2014 Spring, 1.89mm in 2015 Spring, 0.83mm in 2016 Spring and 1.52mm in 2017 Spring), moreover, daily average temperature is a little higher in these two years’ Spring mentioned above. One possible explanation was that SO$_2$ could exacerbate PM$_{2.5}$ formation more easily in this case [24], and in this process, PM10 may have a function of being a reactive site. However, in 2015 Spring and 2017 Spring, SO$_2$O$_3$, O$_3$*T, SO$_2$*T and NO$_2$*T whose contribution rate were more than 2%, occurred when there was more precipitation, which suggested that in Spring, precipitation and temperature may play a positive and catalytic role for SO$_2$, NO$_2$ and O$_3$ contribution rate to PM$_{2.5}$ formation [25, 26]. Wind speed in Jinan during different seasons, its total contribution rate to PM$_{2.5}$ formations all was extremely low, which could be explained by the fact that the unique geographical location of Jinan City, which is surrounded by mountains. In Winter, precipitation was 0.25mm in 2014, 0.27mm in 2015, 1.52mm in 2016 and 0.16mm in 2017, and the sum of precipitation contribution rate were 57.8% in 2014, 79.0% in 2015, 12.9% in 2016 and 3.4% in 2017. It suggested that in Winter more precipitation could alleviate PM$_{2.5}$ pollution, which seems possible that this result was due to rain and snow in Jinan Winter provided more moisture condition in the air [27-29].

There are some limitations in our research. We didn’t focus on hourly data to investigate the association between PM$_{2.5}$ and seasonal factor, meteorological factors and air pollution. In addition, we simply divided one year to four seasons, according to the order of month. Our future work is to research the hourly effect of air pollution on PM$_{2.5}$ formations.

5. Conclusion
It has become an urgent social problem to control PM$_{2.5}$ pollution, improve air quality and protect public health. However, the mechanisms of PM$_{2.5}$ formations has not been figured out. This study aims to identify the effect of critical factors on PM$_{2.5}$ formations in different seasons. We identified that wind speed make a little contribution to PM$_{2.5}$ formations in Jinan during different season. The formation of PM$_{2.5}$ was influenced by a mixture of factors.

Acknowledgements
This study was supported in part by grants from the National Natural Science Foundation (#21728701), the ministry of education postdoctoral fund (#2015M572044), Shandong Province Science and Technology Development Project (#GG201709260070).

References
[1] Z. Guo, Z. Wang, L. Qian, Z. Zhao, C. Zhang, Y. Fu, J. Li, C. Zhang, B. Lu, and J. Qian, "Biological and chemical compositions of atmospheric particulate matter during hazardous haze days in Beijing," Environ Sci Pollut Res Int, 2018-10-12 2018.
[2] D. D. Xie, J. H. Qi and R. F. Zhang, "[Formation and Size Distribution of the Secondary Aerosol Inorganic Ions in Different Intensity of Haze in Qingdao, China]," Huan Jing Ke Xue, vol. 38, pp. 2667-2678, 2017-07-08 2017.
[3] C. Lv, X. Wang, N. Pang, L. Wang, Y. Wang, T. Xu, Y. Zhang, T. Zhou, and W. Li, "The impact of airborne particulate matter on pediatric hospital admissions for pneumonia among children in Jinan, China: A case-crossover study," J Air Waste Manag Assoc, vol. 67, pp. 669-676, 2017-06-01 2017.
[4] M. A. Kioumourtzoglou, J. D. Schwartz, M. G. Weisskopf, S. J. Melly, Y. Wang, F. Dominici, and A. Zanobetti, "Long-term PM2.5 Exposure and Neurological Hospital Admissions in the Northeastern United States," Environ Health Perspect, vol. 124, pp. 23-9, 2016-01-01 2016.
[5] M. Li, Y. Wu, Y. H. Tian, Y. Y. Cao, J. Song, Z. Huang, X. W. Wang, and Y. H. Hu, "Association Between PM2.5 and Daily Hospital Admissions for Heart Failure: A Time-Series Analysis in Beijing," Int J Environ Res Public Health, vol. 15, 2018-10-11 2018.
[6] J. Zhang, Y. Liu, L. L. Cui, S. Q. Liu, X. X. Yin, and H. C. Li, "Ambient air pollution, smog episodes and mortality in Jinan, China," Sci Rep, vol. 7, p. 11209, 2017-09-11 2017.
[7] H. Li, J. Li, H. Li, H. Yu, L. Yang, X. Chen, and Z. Cai, "Seasonal variations and inhalation risk assessment of short-chain chlorinated paraffins in PM2.5 of Jinan, China," Environ Pollut, vol. 245, pp. 325-330, 2018-11-08 2018.

[8] H. Wu, B. Jiang, X. Geng, P. Zhu, Z. Liu, L. Cui, and L. Yang, "Exposure to fine particulate matter during pregnancy and risk of term low birth weight in Jinan, China, 2014-2016," Int J Hyg Environ Health, vol. 221, pp. 183-190, 2018-03-01 2018.

[9] K. L. Chan, S. Wang, C. Liu, B. Zhou, M. O. Wenig, and A. Saiz-Lopez, "On the summertime air quality and related photochemical processes in the megacity Shanghai, China," Sci Total Environ, vol. 580, pp. 974-983, 2017-02-15 2017.

[10] L. J. Shen, L. Li, S. Lu, X. H. Zhang, B. Wu, G. J. Zhang, and F. Wang, "[Observation of a photochemical event in Jinan during summer 2013]," Huan Jing Ke Xue, vol. 35, pp. 1662-70, 2014-05-01 2014.

[11] J. Liu, W. Li, J. Wu, and Y. Liu, "Visualizing the intercity correlation of PM2.5 time series in the Beijing-Tianjin-Hebei region using ground-based air quality monitoring data," PLoS One, vol. 13, p. e0192614, 2018-01-20 2018.

[12] T. Huang, Y. Yu, Y. Wei, H. Wang, W. Huang, and X. Chen, "Spatial-seasonal characteristics and critical impact factors of PM2.5 concentration in the Beijing-Tianjin-Hebei urban agglomeration," PLoS One, vol. 13, p. e0201364, 2018-01-20 2018.

[13] Q. Zhong, J. Ma, G. Shen, H. Shen, X. Zhu, X. Yun, W. Meng, H. Cheng, J. Liu, B. Li, X. Wang, Y. Y. Zeng, D. Guan, and S. Tao, "Distinguishing Emission-Associated Ambient Air PM2.5 Concentrations and Meteorological Factor-Induced Fluctuations," Environmental Science & Technology, vol. 52, pp. 10416-10425, 2018-09-18 2018.

[14] K. Yang, Q. Li, M. Yuan, M. Guo, Y. Wang, S. Li, C. Tian, J. Tang, J. Sun, J. Li, and G. Zhang, "Temporal variations and potential sources of organophosphate esters in PM2.5 in Xinxian, North China," Chemosphere, vol. 215, pp. 500-506, 2018-10-10 2018.

[15] M. Zawacki, K. R. Baker, S. Phillips, K. Davidson, and P. Wolfe, "Mobile Source Contributions to Ambient Ozone and Particulate Matter in 2025," Atmos Environ (1994), vol. 188, pp. 129-141, 2018-09-01 2018.

[16] H. Luo and Z. Lin, "A Dynamic Inversion Model of the Beijing Local Climate," Weather and Forecasting, vol. 29, pp. 614-622, 2014.

[17] S. Qin, J. J. Jiao and S. Wang, "A nonlinear dynamical model of landslide evolution," Geomorphology, vol. 43, pp. 77-85, 2002.

[18] Y. Imaizumi, K. Eguchi and K. Kario, "Coexistence of PM2.5 and low temperature is associated with morning hypertension in hypertensives," Clin Exp Hypertens, vol. 37, pp. 468-72, 2015-01-01 2015.

[19] V. C. Pun, F. Kazemiparkouhi, J. Manjourides, and H. H. Suh, "Long-Term PM2.5 Exposure and Respiratory, Cancer, and Cardiovascular Mortality in Older US Adults," Am J Epidemiol, vol. 186, pp. 961-969, 2017-10-15 2017.

[20] L. L. Liang, J. Y. Sun, Y. M. Zhang, C. Liu, W. Y. Xu, G. Zhang, X. Y. Liu, and Q. L. Ma, "[Comparison of Chemical Components Characteristics of PM2.5 Between Haze and Clean Periods During Summertime in Lin'an]," Huan Jing Ke Xue, vol. 39, pp. 3042-3050, 2018-07-08 2018.

[21] G. Wang, S. Cheng, J. Li, J. Lang, W. Wen, X. Yang, and L. Tian, "Source apportionment and seasonal variation of PM2.5 carbonaceous aerosol in the Beijing-Tianjin-Hebei region of China," Environ Monit Assess, vol. 187, p. 143, 2015-03-01 2015.

[22] S. Wu, F. Deng, Y. Hao, X. Wang, C. Zheng, H. Lv, X. Lu, H. Wei, J. Huang, Y. Qin, M. Shima, and X. Guo, "Fine particulate matter, temperature, and lung function in healthy adults: findings from the HVNR study," Chemosphere, vol. 108, pp. 168-74, 2014-08-01 2014.

[23] J. Lepeule, A. A. Litonjua, A. Gasparri, P. Koutrakis, D. Sparrow, P. S. Vokonas, and J. Schwartz, "Lung function association with outdoor temperature and relative humidity and its interaction with air pollution in the elderly," Environ Res, vol. 165, pp. 110-117, 2018-08-01
2018.

[24] Y. Xie, B. Zhao, L. Zhang, and R. Luo, "Spatiotemporal variations of PM2.5 and PM10 concentrations between 31 Chinese cities and their relationships with SO2, NO2, CO and O3," Particuology, vol. 20, pp. 141-149, 2015.

[25] Y. L. Liu, Q. R. Sun, M. Y. Zhong, B. Q. Zuong, and K. L. Luo, "[Temporal and Spatial Distribution Characteristics of PM2.5 in Chongqing Urban Areas]." Huan Jing Ke Xue, vol. 37, pp. 1219-29, 2016-04-15 2016.

[26] C. Yang, T. Tiyip, Y. J. Hou, Q. Sun, and X. University, "Temporal and spatial variation of PM_ (2.5) and PM_ (10) and the correlation between particulate matters and meteorological factors in east part of Junggar basin," China Mining Magazine, 2016.

[27] S. Yan and G. Wu, "Network Analysis of Fine Particulate Matter (PM2.5) Emissions in China," Sci Rep, vol. 6, p. 33227, 2016.

[28] H. Ikeuchi, M. Murakami and S. Watanabe, "Scavenging of PM2.5 by precipitation and the effects of precipitation pattern changes on health risks related to PM2.5 in Tokyo, Japan," Water Sci Technol, vol. 72, pp. 1319-26, 2015-01-20 2015.

[29] F. Huang, X. Li, C. Wang, Q. Xu, W. Wang, Y. Luo, L. Tao, Q. Gao, J. Guo, S. Chen, K. Cao, L. Liu, N. Gao, X. Liu, K. Yang, A. Yan, and X. Guo, "PM2.5 Spatiotemporal Variations and the Relationship with Meteorological Factors during 2013-2014 in Beijing, China," PLoS One, vol. 10, p. e0141642, 2015-01-20 2015.