Original Research

Analysis on the impact of two winter precipitation episodes on PM$_{2.5}$ in Beijing

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Abstract

In this paper, the circulation background, the characteristics of meteorological elements configuration in the boundary layer and the stable meteorological conditions in two precipitation episodes (during February 19–21, 2015 and February 10–13, 2016, respectively) within the Beijing-Tianjin-Hebei region are compared and analyzed. Data from conventional meteorological observations, air quality monitoring, reanalysis and numerical models are used. The results show that before the two precipitation processes in 2015 and 2016, the circulations in the middle and high latitudes of Asia and Europe demonstrate “two troughs and one ridge”. Besides, the weather is stable and the pollutant concentration is relatively high. During the precipitation, the circulation is relatively stable for the episode in 2015, and no obvious change in the synoptic system is observed. However, during the episode in 2016, the formation of blocking high and the enhancement of the average ridge in western Asia cause obvious change in the circulation. The simulation results show that significant removal can be detected in both cases, and the PM$_{2.5}$ wet deposition fluxes are 647 g/ha and 486 g/ha, respectively, with the removal in 2015 slightly stronger than that in 2016. The removal and dissipation of pollutants is determined by the atmospheric diffusion conditions and the precipitation, especially in the former episode. In the case of February 2016, the removal conditions and the precipitation demonstrate obvious PM$_{2.5}$ removal effect. In the case of February 2015, the longstanding calm wind with high humidity and the physical quantity configuration in the lower mixed layer lead to the poor pollutant removal.

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1. Introduction

With the rapid development of production and economy in China, a large amount of fossil energy has been consumed. At the same time, plenty of polluted gases and soot substances have been discharged into the atmosphere, seriously affecting the atmosphere that human beings survive on. The air qualities [1] and the atmospheric visibilities [2] are low in densely populated urban agglomerations, such as Beijing-Tianjin-Hebei region, Pearl River Delta, Yangtze River Delta and Sichuan Basin, especially the Beijing-Tianjin-Hebei region. Frequent air pollutions are mostly caused by excessive particulate pollutants such as PM$_{2.5}$ and PM$_{10}$ [3,4]. The pollutant deposition in the atmosphere can be mainly divided into dry and wet depositions [5]. Due to the complexity of the precipitation process and the air pollution particles, the removal mechanism of air pollution during the precipitation process needs further study.

Air pollution usually occurs in weak surface pressure systems with low wind speeds and high humidity, and often accompanied by a certain degree of inversion [6,7]. When precipitation occurs in the pollution process, it is usually accompanied by changes in other meteorological elements in the boundary layer. The change trend of pollutant concentration is quite complicated, which may be completely opposite in different precipitation processes due to the simultaneous influences of the wet removal effect and the change of atmospheric diffusion conditions. In addition, the role of wet removal is also closely related to meteorological conditions and pollution levels. The statistical analysis of atmospheric pollutant concentration change before and after precipitation during 2014–2016 in China’s Yangtze River Delta shows that the removal
effect is related to the total amount of rainfall, the average rainfall intensity, the precipitation duration, the background pollutant concentration before precipitation, etc [8–10]. Tai et al. [11] and Chath et al. [12,13] found that there is a strong negative correlation between precipitation and pollutant concentration. Under the same precipitation intensity, when the environmental humidity is 50%, the removal effect is only half of that when the environmental humidity is 95%. Li et al. [14] analyzed the wet removal ability for atmospheric pollutants in different phases of a precipitation episode in Urumqi. It was found that micro-snowfall can increase the concentration of atmospheric pollutants, while micro-rainfall can reduce it. Andronach et al. [5] indicates that the removal efficiency of precipitation is also related to the concentration of aerosol particles, which is higher in the condition of high aerosol concentration.

In terms of wet removal, wet deposition flux can be used to describe the wet deposition of aerosols in the atmosphere. PM2.5 wet deposition flux includes two parts: accretion of cloud droplets containing particles into precipitation and impaction of ambient into precipitation. There are many factors affecting the wet deposition, including the size, concentration, and final velocity of raindrop, as well as raindrop-aerosol particle collision coefficient (Tai et al.,[11]), Pranesh et al., [15] and Bae et al. [16–18] found that the removal efficiency of precipitation on aerosol particles mainly depends on the precipitation intensity, the diameter of raindrops and the size of aerosol particles. When the aerosol particle size is less than 2.2 μm, the removal effect of short-term heavy precipitation is obvious, and when the particle size is larger than 2.2 μm, the removal effect of persistent weak precipitation is better. Mircea et al. [19] and Zhang et al. [20] found that the change of removal coefficient is mainly decided by the size of aerosol particles. The removal coefficient of large particles changes obviously with the diameter of raindrops, while that of small particles is less affected by it.

The impact of the precipitation process on pollutants under different weather conditions needs to be verified and analyzed comprehensively. Specifically, in a relatively weak precipitation episode, there is great uncertainty in the change of pollutant concentration, which is one of the difficulties in air quality forecasting. The pollution days in Beijing are the most in winter, and the heating aggravate the air pollution [21]. Therefore, this paper selects two typical precipitation episodes with wet removal in Beijing-Tianjin-Hebei region in February 2015 and February 2016, takes different meteorological factors into consideration, including relative humidity (%), sea level pressure (hPa), wind speed (m/s), stable weather and transmission conditions, and explores and compares the wet removals under different weather conditions through simulation analysis.

2. Materials and method

2.1. Sources

In this paper, two precipitation episodes in Beijing during February 19–21, 2015 and February 10–13, 2016 are selected. The PM2.5 mass concentration data come from the average values of several state-controlled environmental monitoring sites in Beijing (including Olympic Sports Center, Wanliu in Haidian District, Agricultural Exhibition Center, Dongsi, Guanyuan, Gucheng, the Temple of Heaven and Wanshou West Palace), which can be achieved on the website of China Environmental Monitoring Station (http://www.cnemc.cn/), with a temporal resolution of 1 h. The data of meteorological elements (including temperature, humidity, wind speed, wind direction, visibility, etc.) in this paper come from the averages of the National Meteorological Administration Encrypted Observation Station, and the temporal resolution is 1 h. The number of selected points is consistent with that of national environmental monitoring points. By using the minimum radius method, the location of the nearest station is determined one by one. In addition, the FNL reanalysis data (http://rda.ucar.edu/datasets/ds083.2/) provided by NCEP (National Center for Environmental Prediction of the United States) with a spatial resolution of $1^\circ \times 1^\circ$ and a temporal resolution of 6 h are also used.

2.2. Mixed layer height algorithms

The height of mixed layer represents the height that pollutants can be transported by thermal convection and dynamic turbulence vertically. It is an important parameter affecting pollutant diffusion, and it is closely related to atmospheric stability and wind speed. The higher the mixed layer is, the more conducive it is to pollutant diffusion in the vertical direction, and vice versa. In this paper, the Roche method [22,23] is used to calculate the height of mixed layer. It is a method proposed by Nozaki et al., in 1973 to estimate the height of mixed layer by using surface meteorological data. The calculation formula is as follows:

$$MLH = \frac{121}{6} (6 - Pas)(T - T_d) + \frac{0.169 Pas(U_z + 0.257)}{12f \ln(Z/Z_0)}$$

where MLH is the mixed layer height (m), (T-Td) is the temperature-dewpoint difference (K), $U_z$ is the average wind speed (m/s) at height Z, $Z_0$ is the surface roughness (m), f is geostrophic parameter (1/s), and Pas is the Pasquill stability level (the classification of the atmospheric stability according to ground observation data, thermal and dynamic factors, quantitatively classified solar altitude angle, cloud amount and wind speed).

2.3. Numerical model method

In this paper, the meteorological fields from the WRF (Weather Research and Forecasting Model) model are used to drive the Comprehensive Air Quality Model with Extensions (CAMx) air quality model, and the pollutant wet deposition during the two removal processes is simulated and analyzed. The initial boundary conditions of the WRF model are based on the global reanalysis data (FNL) of NCEP with resolution of $1^\circ \times 1^\circ$ which are input 6-hourly. The Dudhia short-wave radiation scheme, the RRTM long-wave radiation scheme, the Unified Noah pavement scheme and the YSU boundary layer parameterization scheme are selected for the parameterization of the physical process in the model. Three nested domains are used in the simulation, with horizontal resolutions of 36 km, 12 km and 4 km, respectively. The first domain covers most of China, the second one covers the Beijing-Tianjin-Hebei region and the surrounding areas, and the third one covers Beijing and its surrounding areas. The atmospheric chemical model CAMx6.2 simulates the atmospheric chemical process [24]. CB05 mechanism is chosen as the gas phase chemical mechanism. The Seinfeld [25] method is referred to for the removal of aerosols by precipitation in the model. The anthropogenic emission inventory of pollutants in the Beijing-Tianjin-Hebei region and the surrounding areas are based on the MEIC emission source inventory of Tsinghua University in 2016 (http://www.meicmodel.org). Neural emission is calculated by the Biogenic Emissions Inventory System version 3 (BEIS3) within the Sparse Matrix Operator Kernel Emissions (SMOKE) modelling system (SMOKE) model.
3. Results and discussion

3.1. Overview of the two heavily polluted weather episodes in 2015 and 2016

Two polluted weather episodes with precipitation in Beijing during February 18–21, 2015 and February 10–13, 2016 are chosen in this paper. The change trends of PM$_{2.5}$ mass concentration affected by precipitation are significantly different in the two episodes. Firstly, the synoptic situation and pollution situation of the two episodes are briefly compared and analyzed.

Since February 18, 2015, the circulation in the middle and high latitudes of Asia and Europe has gradually evolved into the pattern of two troughs and one ridge. The upper altitudes in most parts of central and eastern China are controlled by the uniform westerly airflow. The formation of warm ridges in the 850 hPa height field extends the inversion layer upwards and generates a dry warm core over Beijing and other areas. The Beijing-Tianjin-Hebei region and its surrounding areas are located behind the surface high, with sparse isobars and small pressure gradients, and the horizontal diffusion of air pollution is relatively weak. At the same time, the low-level atmospheric convergence zone sways slowly from south-central Hebei Province to north-central Henan Province, and water vapor and pollutants accumulate gradually near the ground. At 16:00 on the 19th, the PM$_{2.5}$ concentration grows to 110 μg/m$^3$ (Fig. 1). At that time, North China is affected by the low system near the ground. A deep low trough in the middle and lower troposphere advances from west to east, and there is a near surface cold front with abundant water vapor, which passes at 18:00 on the 19th. The cold air behind the front raises and condenses the warm and humid air, causing precipitation. The precipitation episode lasts for 23 h, with the cumulative precipitation of 9.3 mm and the average rainfall intensity of 0.4 mm. The maximum precipitation intensity (1.2 mm/h) appears at 05:00 on the 20th. During the precipitation, the surface relative humidity increases rapidly and maintains over 90%. Two lower values of PM$_{2.5}$ mass concentration in Beijing appear at 06:00 and 11:00 on the 20th, which are 91 μg/m$^3$ and 93 μg/m$^3$, respectively. Then the PM$_{2.5}$ mass concentration increases rapidly, with an increase rate of 11 μg/m$^3$/h. At the end of the precipitation episode (17:00 on the 20th), the PM$_{2.5}$ mass concentration increases to 145 μg/m$^3$ rapidly. At 20:00 on the 21st, the main body of the cold high arrives in Beijing, and the northerly wind near the ground gradually increases. The PM$_{2.5}$ mass concentration decreases to a relatively low level, and then the pollution ends. The pollutant concentration does not decrease significantly before or after the precipitation, but increases in some other periods. The wet removal effect of precipitation is not evident in the PM$_{2.5}$ concentration reduction.

Another polluted weather episode occurs in Beijing from February 10 to 13, 2016. During the pollution accumulation, the circulation situation of two troughs and one ridge maintains in the middle and high latitudes of Asia (500 hPa) (Fig. 2d). Most parts of North China are controlled by the weak high ridge, and the weather is stable. Beijing is controlled by a low convergence zone. The pollutant diffusion ability is poor, and the PM$_{2.5}$ accumulates continuously near the ground. At 10:00 on the 12th, the PM$_{2.5}$ mass concentration exceeds 150 μg/m$^3$. Affected by the trough moving eastward, the sea level pressure gradient gradually increases, and the cold front arrives in Beijing at 16:00 on December 12. With the impact of low-level shear line and frontal cyclone, the precipitation occurs in North China. In the early stage of the precipitation (16:00–21:00 on the 12th), the average precipitation intensity in Beijing is less than 1 mm, and the PM$_{2.5}$ is still in a continuous accumulation. The peak PM$_{2.5}$ concentration of 240 μg/m$^3$ appears at 20:00. When the frontal surface arrives in Beijing at 21:00, the precipitation intensity increases, and the maximum rainfall intensity reaches 1.4 mm (22:00 on the 12th). At the same time, the surface wind accelerates and the PM$_{2.5}$ mass concentration drops sharply, from 240 μg/m$^3$ to below 75 μg/m$^3$ in 2 h. The precipitation lasts until 06:00 on the 13th (Fig. 2f) when the PM$_{2.5}$ mass concentration is only 5 μg/m$^3$.

Precipitation occurs during the two polluted weather episodes, and there is little difference in the PM$_{2.5}$ concentration before the precipitation, with the concentration in 2016 (168 μg/m$^3$) slightly higher than that in 2015 (125 μg/m$^3$). The evolution of atmospheric circulation during the episode of 2015 is more stable than that of 2016. The synoptic system during the precipitation does not change obviously, and the precipitation intensity is slightly lower than that in 2016. Despite the same precipitation conditions, the change trends of pollutant concentration in the two polluted weather episodes are quite different. In order to find out the reasons, the main meteorological elements and the static weather conditions in the boundary layer during the two episodes are compared, and the wet removal wet depositions of the two episodes are simulated and analyzed.

3.2. Contrastive analysis of meteorological elements in the two wet removal processes

According to the wind profiles in the boundary layer in the two precipitation episodes in Beijing (Fig. 3), it can be seen that the southwest wind is prevalent below 1800 m from February 19 to 20, 2015. Despite the weak precipitation during this period, the humidification effect caused by the weak precipitation and the influence of southwest wind in the boundary layer increase the corresponding surface PM$_{2.5}$ concentration, thus there is no obvious wet removal. It is at the night of 21st that the main cold air significantly affects Beijing. From February 10 to 12, 2016, the pollutant concentration does not change significantly under the control of the northeast wind. However, since 16:00 on February 12, weak precipitation occurs in Beijing. During the precipitation, the upper cold air gradually grounds, and the atmospheric diffusion conditions and the air quality are greatly improved.

![Fig. 1. Changes of pollutant concentration and hourly rainfall during the two wet removal processes.](image-url)
By comparing the physical quantities in the boundary layer in the two episodes (Fig. 4), it is found that the average height of the mixed layer is 297.6 m and the average wind speed is 1.4 m/s in February 2015. The lower height of the mixed layer and the weaker 10-m wind worsen the local vertical and horizontal diffusion conditions, which is conducive to the accumulation of local pollutants in the near-surface layer. In addition, the high relative humidity lasts for a long time, with the average value reaching 82%, and the dry deposition condition is poor. In the precipitation wet removal, the characteristic physical quantities are relatively stable. During the precipitation, the maximum height of mixed layer is only 135.3 m. The maximum wind speed is 1 m/s and the relative humidity is above 95%. The PM$_{2.5}$ concentration is 180 µg/m$^3$, and the heavy pollution is not significantly reduced. In February 2016, the average height of the mixed layer reaches 468.9 m. The average wind speed is 2.4 m/s, the average relative humidity is 85.5%, which drops to 63% after the precipitation wet removal, and the PM$_{2.5}$ concentration is reduced to 16 µg/m$^3$. As a result, the pollutant concentration decreases significantly with the increase of mixed layer height, the increase of 10-m wind speed and the decrease of relative humidity. Compared with the episode in 2015, this episode shows higher mixed layer height and larger wind speed, and there is no sustained high relative humidity, which provides good vertical and horizontal diffusion conditions for the pollutant removal. Overall, the precipitation episode in February 2016 is controlled by clean upper-level subsidence air masses along the northward path. The dry air, which is conducive to the dilution and diffusion of pollutants, works with the precipitation, and good wet removal effect is achieved. During the precipitation episode in February 2015, the persistent southerly airflow in the lower-level atmosphere is conducive to the transport of atmospheric particulates from the heavily polluted areas of central and southern Hebei to Beijing. The accumulation of pollutants offsets a part of the wet removal, so the wet removal effect is not obvious. The pollutant

![Fig. 2. Height field (contour, unit: dagpm) and mean sea level pressure field (shading, unit: hPa) at 500 hPa at (a) 20:00 on Feb. 19, 2015, (b) 20:00 on Feb. 20, 2015, (c) 20:00 on Feb. 21, 2015, (d) 08:00 on Feb. 12, 2016, (e) 20:00 on Feb. 12, 2016 and (f) 08:00 on Feb. 13, 2016.](image)
concentration even rebounds in the late stage of the wet removal. In a short time, the local emission sources in Beijing can be regarded as relatively stable quantities. When the local source is relatively stable, the wind direction has become an important factor affecting the source of pollution in Beijing. On the one hand, the air pollution in central and southern Hebei is relatively serious, and the industrial distribution is relatively dense. When Beijing has a continuous southerly wind, it is conducive to the transportation of pollutants from Hebei to Beijing. In the area on the north of Beijing, the industrial sources are in low level. When the northerly wind prevails, the air mass that flows into Beijing is relatively clean. On the other hand, the northerly wind direction is usually accompanied by cold air activity, the wind speed is higher, and the atmospheric diffusion conditions are better. However, the wind speed in southerly direction is usually low, and the atmosphere is relatively stable, which is conducive to the accumulation of pollutants. During the precipitation in 2015, although the wind direction changed to a certain extent during the precipitation period (the wind direction is southeast in the early period of precipitation, and change to easterly in the later period), the main wind frequency is still southerly, and the atmosphere is relatively stable during the entire precipitation period, which is conducive to the accumulation of pollutants. However, during the precipitation process in 2016, after the beginning of precipitation, the wind direction changed from southerly to northeasterly, and further changed to northwesterly with the wind speed increased. On the one hand, better diffusion conditions are conducive to the dissipation of local pollutants. At the same time, the air mass brought by the northerly wind is cleaner and the PM$_{2.5}$ concentration is rapidly reduced. Under the combined effect, the PM$_{2.5}$ concentration rapidly decreases.

3.3. Simulation and analysis of removal wet deposition

In order to further compare the removal effect of precipitation on PM$_{2.5}$, the WRF-CAMx model is used to simulate the changes of PM$_{2.5}$ concentration and wet deposition flux during the two precipitation episodes. Fig. 5 shows the simulated changes of PM$_{2.5}$ concentration and wet deposition in the two episodes. Compared with the observation, the simulation can basically reflect the changes of PM$_{2.5}$ concentration during the two episodes with high correlation coefficients ($R^2$: 0.75 and 0.91) and low mean biases (3.1 $\mu$g/m$^3$ and -15.2 $\mu$g/m$^3$) (see Table 1).

Fig. 6 shows the difference between the total amount of wet removal during these two episodes. In most areas of Beijing, the removal of aerosols during February 19–21, 2015 is greater than that during February 10–12, 2016. In the precipitation episode of 2016, the PM$_{2.5}$ concentration has decreased to below 50 $\mu$g/m$^3$ before the precipitation increases due to the cold air. During the precipitation, the wet deposition flux of PM$_{2.5}$ in Beijing is 486 g/ha. However, during the precipitation episode in 2015, there is no cold air affecting...
Beijing, and uniform southerly wind is dominant on the surface, which maintains the PM$_{2.5}$ concentration above 100 $\mu$g/m$^3$ during the whole episode. The wet deposition flux of PM$_{2.5}$ in Beijing during the precipitation is 647 g/ha. The average of hourly removal concentrations (Table 2) were 4.9 and 3.7 $\mu$g/m$^3$ for the two episode in 2015 and 2016. The average of hourly removal rates were 6.8% and 5.3%, and the max hourly removal rates were 7.9% and 13.8%, for the two episode in 2015 and 2016 respectively. The max of hourly removal rate and concentration for the episode in 2016 was much higher than the episode in 2015, because there was higher PM$_{2.5}$ concentrations blow the cloud and heavier rainfall for episode in 2016 than in 2015. The change of deposition flux in Fig. 5 further indicates that the deposition flux during the precipitation episode in 2015 lasts longer than that in 2016, therefore the total deposition flux is still smaller than that in the episode of 2015. In conclusion, there are obvious wet removals in both episodes, but the wet removal effect in the episode of 2015 is better than that in 2016.

In addition, by comparing the surface wind field and the relative humidity in the Beijing-Tianjin-Hebei region at the initial time of the two wet removal processes, and the peak concentration of PM$_{2.5}$ at the end of the precipitation episodes (Fig. 7), it can be seen that the high humidity area (RH > 60%) in the initial stage of the wet removal is smaller in the 2015 case. With the continuation of the precipitation, the area of large relative humidity rapidly increases and spreads to the whole area. In the period with most pollution, the surface wind field is dominated by calm wind or weak southeast wind. The PM$_{2.5}$ concentration in Beijing maintains at 100–130 $\mu$g/m$^3$, without significant change. In the initial stage of the wet removal in 2016, the relative humidity in the region is higher. However, with the continuation of the precipitation, the growth rate of relative humidity is significantly lower than that in 2015. During the precipitation, the mean value of surface relative humidity and the range of high humidity area are both smaller than those in 2015, but the average relative humidity in most areas of the region is generally higher than 80%, promoting the moisture absorption and growth of aerosol particles. What’s more, during the wet removal, an obvious wind direction convergence appears in the surface wind field in eastern Beijing, which promotes the accumulation of more pollutants. The PM$_{2.5}$ concentration shows an upward trend after the precipitation. Therefore, in both cases of 2016 and 2015, after the precipitation, the surface meteorological elements (wind field, relative humidity) are conducive to the accumulation of pollutants, which offsets the precipitation removal of pollutants in various degrees. The pollutant concentration increases instead of decreasing.

Therefore, comprehensive observation and simulation results show that good diffusion conditions and precipitation in the case of 2016 contribute to the obvious PM$_{2.5}$ removal. While in the case of 2015, the longstanding calm wind with high humidity and the physical quantity configuration in the lower mixed layer are important factors causing the poor wet removal. The cooperation between the atmospheric diffusion conditions and the precipitation process determines the wet removal effect in the polluted weather.

4. Conclusions

In this paper, two polluted weather episodes in the Beijing-Tianjin-Hebei region during February 19–21, 2015 and February 10–13, 2016 are analyzed. The similarities and differences of precipitation wet removals in the two episodes are compared and analyzed. The results are as follows.

(1) Before the two wet removal processes in 2015 and 2016, the circulation pattern in the middle and high latitudes of Asia and Europe demonstrates two troughs and one ridge. The weather is stable and the pollutant concentration is high. During the precipitation, the general circulation situation...
during the episode in 2015 is relatively stable, with no obvious change in the weather system. However, during the precipitation episode in 2016, the blocking high forms and the average ridge in Western Asia strengthens, resulting in the strong evolution of atmospheric circulation.

(2) The simulation results show that wet removal appears in both episodes. The wet deposition fluxes of PM$_{2.5}$ in Beijing during the two precipitation episodes are 647 g/ha and 486 g/ha, respectively. The wet removal effect in the episode of 2015 is slightly stronger than that in 2016.

(3) The main reason for the significant change of PM$_{2.5}$ is the cooperation between the change of atmospheric diffusion conditions and the precipitation wet removal. In the case of 2016, good diffusion conditions and precipitation combine to create the obvious PM$_{2.5}$ removal. While in the case of 2015, the longstanding calm wind with high humidity and the physical quantity configuration in the lower mixed layer cause the poor removal of PM$_{2.5}$. Although both episodes have obvious wet removal effect, the change of atmospheric diffusion conditions determines the PM$_{2.5}$ removal effect.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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References

[1] J. Song, T. Cheng, Z.Q. Xie, et al., Impact on spatio-temporal variation of fog and haze days due to rapid urbanization in Jiangsu (in Chinese), Scientia Meteorologica Sinica(in Chinese) 32 (3) (2012) 275–281.

[2] X. Ye, A.J. Jiang, J. Zhang, et al., Analysis of characteristics and trends of atmospheric visibility in Nanjing (in Chinese), Scientia Meteorologica Sinica(in Chinese) 31 (3) (2011) 325–331.

[3] C. Gao, T.J. Wang, J.J. Wu, et al., Study on a continuous haze weather event during autumn of 2009 in Nanjing(in Chinese), Scientia Meteorologica Sinica(in Chinese) 32 (3) (2012) 246–252.

[4] D.Y. Liu, J. Zhang, X.P. Wu, et al., Characteristics and sources of atmospheric pollutants during a fog-haze process in Huai'an (in Chinese), Transactions of Atmospheric Sciences(in Chinese) 37 (4) (2014) 484–492.

[5] C. Andronache, T. Gronholm, L. Laakso, et al., Scavenging of ultrafine particles by rainfall at a Boreal Site: observations and model estimations, Atmos. Chem. Phys. 6 (2006) 4739–4754.

[6] Q. Jiang, Y.L. Sun, Z. Wang, Y. Yin, Aerosol composition and sources during the Chinese Spring Festival: fireworks, secondary aerosol, and holiday effects, Atmos. Chem. Phys. 15 (2015) 6023–6034, https://doi.org/10.5194/acp-15-6023-2015.

[7] Y. Sun, et al., Aerosol characterization over the North China Plain: haze life cycle and biomass burning impacts in summer, J. Geophys. Res.: Atmosphere 121 (5) (2016) 2508–2521, https://doi.org/10.1002/2015JD024261.

[8] L.C. An, H.D. Zhang, K.F. Li, Analysis of effect of precipitation events on air pollutant concentration (in Chinese), Journal of Meteorology and Environment Dynamics 34 (3) (2018) 58–70.

[9] G.B. Zhou, Studies of the Influence of Meteorological Factors on Air Pollution and its Numerical Simulation in the Main Urban Region of Chongqing(in Chinese), Lanzhou University, Lanzhou, 2014.

[10] H. Zhou, D.Y. Liu, J.S. Wei, et al., Preliminary analysis on scavenging effect of precipitation on aerosol particles(in Chinese), Resour. Environ. Yangtze Basin 1 (2015) 160–170.

[11] A.P.K. Tai, L.J. Mickley, D.J. Jacob, 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. 44 (32) (2010) 3976–3984.

[12] D.M. Chath, P.S.P. Rao, M.S. Naik, et al., Scavenging of aerosols and their chemical species by rain, Atmos. Environ. 37 (18) (2003) 2477–2484.

[13] D.M. Chath, T.S. Pranesha, Field studies of scavenging of aerosols by rain events, J. Aerosol Sci. 35 (6) (2004) 695–706.

[14] X. Li, Q. Yang, Y. Wu, Comparison of wet removal efficiency between snow and rain to aerosol particles in urumqi region (in Chinese), J. Desert Res. 23 (5) (2003) 560–564.

[15] T.S. Pranesha, A.K. Kamra, Scavenging of aerosol particles by large water drops: 3. Washout coefficients, half-lives, and rainfall depths, J. Geophys. Res.: Atmosphere 102 (D20) (1997) 23947–23953, 1984-2012.

[16] S.Y. Bae, H.J. Chang, P.K. Yong, Relative contributions of individual phoretic effects in the below-cloud scavenging process, J. Aerosol Sci. 40 (7) (2009) 621–632.

[17] S.Y. Bae, H.J. Chang, P.K. Yong, Derivation and verification of an aerosol dynamics expression for the below-cloud scavenging process using the moment method, J. Aerosol Sci. 41 (3) (2010) 266–280.

[18] S.Y. Bae, R.J. Park, Y.P. Kim, et al., Effects of below-cloud scavenging on the regional aerosol budget in East Asia (J), Atmos. Environ. 58 (2012) 14–22.

[19] M. Mircea, S. Stefan, S. Fuzzi, Precipitation scavenging coefficient: influence of measured aerosol and raindrop size distributions, Atmos. Environ. 34 (29/30) (2000) 5169–5174.

[20] L.M. Zhang, D.V. Michelangeli, P.A. Taylor, Numerical studies of aerosol scavenging by low-level, warm stratiform clouds and precipitation, Atmos. Environ. 38 (28) (2004) 4653–4665.

[21] Q. Wang, Y. Sun, W. Xu, W. Du, L. Zhou, G. Tang, C. Chen, X. Cheng, X. Zhao, D. Ji, Vertically-resolved characteristics of air pollution during two severe winter haze episodes in urban beijing, China, Atmos. Chem. Phys. 18 (4) (2018) 1–28.

[22] X.N. Liao, X.L. Zhang, Y.C. Wang, et al., Comparative analysis on meteorological condition for persistent haze cases in summer and winter in beijing, Environ. Sci. 35 (6) (2014) 2031–2044.

[23] J. Li, S.C. You, J.F. Huang, Spatial distribution of ground roughness length based on GIS in China, J. Shanghai Jiaot. Univ. 24 (2) (2006) 185–189.

[24] ENVIRON, User’s guide to the comprehensive air quality model with Extensions (CAMx), Version 6.2 (M), 2015. Available at: http://www.camx.com.