Optical Properties of Aerosols and Chemical Composition Apportionment under Different Pollution Levels in Wuhan during January 2018

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Abstract: To clarify the aerosol optical properties under different pollution levels and their impacting factors, hourly organic carbon (OC), elemental carbon (EC), and water-soluble ion (WSI) concentrations in PM$_{2.5}$ were observed by using monitoring for aerosols and gases (MARGA) and a semicontinuous OC/EC analyzer (Model RT-4) in Wuhan from 9 to 26 January 2018. The aerosol extinction coefficient ($b_{ext}$) was reconstructed using the original Interagency Monitoring of Protected Visual Environment (IMPROVE) formula with a modification to include sea salt aerosols. A good correlation was obtained between the reconstructed $b_{ext}$ and measured $b_{ext}$ converted from visibility. $b_{ext}$ presented a unimodal distribution on polluted days (PM$_{2.5}$ mass concentrations > 75 μg·m$^{-3}$), peaking at 19:00. $b_{ext}$ on clean days (PM$_{2.5}$ mass concentrations < 75 μg·m$^{-3}$) did not change much during the day, while on polluted days, it increased rapidly starting at 12:00 due to the decrease of wind speed and increase of relative humidity (RH). PM$_{2.5}$ mass concentrations, the aerosol scattering coefficient ($b_{scat}$), and the aerosol extinction coefficient increased with pollution levels. The value of $b_{ext}$ was 854.72 Mm$^{-1}$ on bad days, which was 4.86, 3.1, 2.29, and 1.28 times of that obtained on excellent, good, acceptable, and poor days, respectively. When RH < 95%, $b_{ext}$ exhibited an increasing trend with RH under all pollution levels, and the higher the pollution level, the bigger the growth rate was. However, when RH > 95%, $b_{ext}$ on acceptable, poor and bad days decreased, while $b_{ext}$ on excellent and good days still increased. The overall $b_{ext}$ in Wuhan in January was mainly contributed by NH$_4$NO$_3$ (25.2%) and organic matter (20.1%). The contributions of NH$_4$NO$_3$ and (NH$_4$)$_2$SO$_4$ to $b_{ext}$ increased significantly with pollution levels. On bad days, NH$_4$NO$_3$ and (NH$_4$)$_2$SO$_4$ contributed the most to $b_{ext}$, accounting for 38.2% and 27.0%, respectively.

Keywords: Wuhan; MARGA; IMPROVE formula; relative humidity

1. Introduction

In recent years, air quality deterioration and visibility impairment have occurred in many urban areas of China [1–4]. One of the key pollutants is PM$_{2.5}$ (aerosol particle with aerodynamic diameter less than 2.5 μm), which has a great effect on visibility impairment, urban air quality, and human health [5–7]. PM$_{2.5}$ is mainly composed of organic and inorganic components and is typically hygroscopic. The size of PM$_{2.5}$ can increase under high relative humidity (RH) conditions, therefore...
influencing the aerosol optical properties and leading to an increase in the aerosol scattering coefficient \( (b_{\text{sc}}) \) and aerosol extinction coefficient \( (b_{\text{ext}}) \) [8,9].

PM\(_{2.5}\) in the atmosphere can reduce visibility through light extinction (including scattering and absorption of light) and also plays an important role in the formation of haze in urban areas [10,11]. The aerosol extinction coefficient \( (b_{\text{ext}}) \) is an important parameter of atmospheric extinction and is particularly significant in aerosol optical research. \( b_{\text{ext}} \) is mainly contributed by (NH\(_3\))\(_2\)SO\(_4\), NH\(_4\)NO\(_3\), organic matter (OM), elemental carbon (EC), sea salt, coarse mass, and so on. Their relative contributions to \( b_{\text{ext}} \) vary with time and location. The Interagency Monitoring of Protected Visual Environment (IMPROVE) formula is a method for calculating the aerosol extinction coefficient \( (b_{\text{ext}}) \) based on the chemical composition of a substance [12,13]. Many scholars have used it to calculate the contribution of each particle component to the extinction coefficient. Existing studies have found that in urban areas, (NH\(_3\))\(_2\)SO\(_4\) was the largest contributor to \( b_{\text{ext}} \), followed by NH\(_4\)NO\(_3\) and OM [14–17]. Combustion-related particles rather than wind-blown dust dominated the light extinction budget in Beijing [18]. The contributions of sulfate, ammonium, and nitrate to the PM\(_{2.5}\) mass concentration were 15%, 5%, and 8%, respectively. Mineral aerosol contributed 16% to the PM\(_{2.5}\) aerosol mass, showing that combustion-related particles rather than wind-blown dust dominated the light extinction budget [19]. The seasonally reconstructed \( b_{\text{ext}} \) was in the order of autumn (319.4 ± 207.2 Mm\(^{-1}\)) > winter (269.6 ± 175.5 Mm\(^{-1}\)) > summer (219.0 ± 129.3 Mm\(^{-1}\)) > spring (193.3 ± 94.9 Mm\(^{-1}\)) annually in Guangzhou [20]. RH is an important meteorological factor in the atmosphere and has a notable effect on the formation and optical properties of PM\(_{2.5}\). RH is a key factor in visibility impairment that affects light extinction through the hygroscopic growth of particles [21,22]. \( b_{\text{ext}} \) values were higher in higher humidity conditions [23,24]. High RH played an important role in the formation of PM\(_{2.5}\). However, when RH > 80%, PM\(_{2.5}\) concentrations began to decrease due to the high frequency of precipitation [25,26].

In recent years, many studies have been performed to investigate aerosol optical properties in many developed cities in China, such as Nanjing [22,27], Beijing [18,28,29], Guangzhou [20,25], and Chengdu [14,30]. In addition, many studies have been done to determine the relationship between aerosol optical properties and pollution level. The atmospheric extinction coefficient \( (b_{\text{ext}}) \) and the absorption coefficient of aerosols \( (b_{\text{abs}}) \) increased, and the single scattering albedo (SSA) decreased from excellent to polluted levels [31]. Higher aerosol optical depth (AOD) and SSAs were observed during polluted periods than during non-polluted periods [32]. However, studies in Wuhan about aerosol optical properties under different pollution levels are very limited.

As the capital of Hubei province, Wuhan covers an area of 8500 square kilometers. The permanent resident population was 10.90 million in 2017. In recent years, with the rapid development of economy and the acceleration of urbanization, haze pollution in Wuhan is increasingly serious. Therefore, many studies have been done in Wuhan. PM\(_{2.5}\) was the primary pollutant, and O\(_3\) was the secondary pollutant, in Wuhan as determined by calculating the value of the Individual Air Quality Index (IAQI) [33]. The major chemical compositions of PM\(_{2.5}\) were investigated in Wuhan, and it was found that OM was the most abundant component in PM\(_{2.5}\), the lowest concentrations of which were observed in summer [34]. Regional chemical transport played an important role in both short-term haze episodes and persistent haze episodes that occurred in Wuhan [35]. The physical and chemical characteristics, including chemical composition, hygroscopicity, and particle size distribution of aerosols are quite different under different pollution levels. In addition, the meteorological conditions (RH, wind speed, wind direction, and stability) are also different under different pollution levels. Therefore, the contribution of aerosol chemical components to the light extinction is different under different pollution levels. To gain a thorough knowledge of aerosol optical properties under different pollution conditions, the values of hourly concentrations of PM\(_{2.5}\), water-soluble ions (WSIs), organic carbon (OC), elemental carbon (EC), and meteorological parameters were observed in Wuhan during January 2018. \( b_{\text{ext}} \) was reconstructed based on the IMPROVE formula, and the reconstructed \( b_{\text{ext}} \) was used to assess the contributions of individual components of PM\(_{2.5}\) to the total light extinction. In this study, aerosol optical parameters under different pollution levels were compared and analyzed. The influence of meteorological factors on optical parameters was also discussed.
2. Materials and Methods

2.1. Data Origins

As the central city of central China, Wuhan is located in the eastern part of Hubei province, at the intersection of the Yangtze River and Hanshui. Wuhan is covered by rivers and lakes, and water accounts for about a quarter of the total area of the city. According to the statistical bulletin of Wuhan national economic and social development in 2017, the annual GDP of Wuhan had reached 134.10 billion yuan by the end of 2017, which was an increase of 8.0% over the previous year. The annual average concentrations of ambient fine particulate matter (PM$_{2.5}$) and inhalable particulate matter (PM$_{10}$) were 52 µg·m$^{-3}$ and 87 µg·m$^{-3}$, respectively, which were 8.8% and 5.4% lower than those of the previous year. Wuhan has a north subtropical monsoon climate and experiences abundant rainfall and sufficient heat annually. The city is relatively hot in the summer and cold in the winter. The observation time was from January 9 to January 26, 2018. All time mentioned in this passage were local time, and the time of sunset was 17:30 in January in Wuhan.

2.2. Instruments

Water-soluble ions (NO$_3^-$, SO$_4^{2-}$, Cl$^-$, Ca$^{2+}$, and Mg$^{2+}$) were measured using a model ADI 2080 monitor in ambient air (MARGA, Applikon Analytical B.V., the Netherlands) with a Teflon-coated PM2.5 sampling inlet at an hourly temporal resolution. For detailed principles of the tool, please refer to related articles [36–41].

A semicontinuous thermal-optical transmittance (TOT) carbon analyzer (Model RT-4, Sunset Laboratory Inc., Tigard, OR, USA) was used to measure the hourly concentrations of OC and EC. The affirmation of the Sunset field carbon analyzer can be found in related reference [35,36]. Each measurement cycle is composed of 45 min of sampling and 15 min of OC/EC analysis. The detailed principle of the instrument can be found in other literature [37].

Hourly concentrations of PM$_{2.5}$, PM$_{10}$ and NO$_2$ were downloaded from the Ministry of Ecology and Environment (MEE) of China website (http://106.37.208.233:20035/), Zhuankou district station (114°150 E, 30°470 N). The meteorological data (temperature, wind speed, wind direction, relative humidity) were measured from the Wuhan meteorological station (114.03° E, 30.36° N).

2.3. Data Analysis

The black carbon (BC) mass concentrations were used to calculate the $b_{abs}$ as follows:

$$b_{abs} = \alpha \times [BC]$$  \hspace{1cm} (1)

where $\alpha$ is a conversion factor. The value of $\alpha$ was 8.28 m$^2$·g$^{-1}$ based on a comparison test between the Aethalometer and the photoacoustic spectrometer in southern China [42]. BC mass concentrations were replaced by EC mass concentrations. $b_{abs}$ is absorption coefficient of particles (unit: Mm$^{-1}$).

In this study, two methods were used to calculate $b_{ext}$. One method used the visibility data, which were converted to $b_{ext}$ using the Koschmeider equation [43]:

$$b_{ext} = 3912/VR(2),$$ \hspace{1cm} (2)

where VR represents visual range (unit: km), and $b_{ext}$ represents the aerosol extinction coefficient (unit: Mm$^{-1}$). Another method was to calculate $b_{ext}$ using the IMPROVE formula:

$$b_{ext} = 3 \times f(RH) \times [(NH_4)_2SO_4] + 3 \times f(RH) \times [(NH_4)NO_3] + 4 \times [OM] + 10 \times [EC]$$
$$\quad + 1 \times [Soil] + 1.7 \times f(RH) \times [SS] + 0.6 \times [CoarseMass]$$
$$\quad + 0.33 \times [NO_2] + Rayleigh\, Scattering$$ \hspace{1cm} (3)

where [x] represents the concentration of constituent x (unit: µg·m$^{-3}$). [(NH$_4$)$_2$SO$_4$] was replaced by 1.375 times [SO$_4^{2-}$], [(NH$_4$)NO$_3$] was replaced by 1.29 times [NO$_3^-$], [OM] was replaced by 1.6 times [OC], [Soil] was replaced by the sum of 1.63 times [Ca$^{2+}$] and 1.67 times [Mg$^{2+}$], and [SS] was replaced by 1.8-times [Cl$^-$]. [CoarseMass] could be replaced by [PM$_{10}$], the unit of [NO$_2$] is 10$^{-6}$, and Rayleigh Scattering was replaced by 10. f(RH) is the hygroscopic growth factor [8].

Therefore, \( b_{\text{scat}} \) can be obtained from a difference between \( b_{\text{ext}} \) and \( b_{\text{abs}} \):

\[
b_{\text{scat}} = b_{\text{ext}} - b_{\text{abs}}
\] (4)

Figure 1 shows the comparison of \( b_{\text{ext}} \) between the two methods, and a fair correlation was observed between the two sets of \( b_{\text{ext}} \), with a correlation coefficient (R) of 0.6; the number of samples (N) was 211. This finding suggests that the reconstructed \( b_{\text{ext}} \) using the IMPROVE formula can be used for later analysis.

![Figure 1. Relationship of \( b_{\text{ext}} \) based on two methods.](image)

### 3. Results and Discussion

#### 3.1. Summary of a Haze Episode

According to newly released ambient air quality standards in 2012, in China, air quality conditions can be classified into five categories. According to PM\(_{2.5}\) mass concentrations from the best to worst were: excellent (PM\(_{2.5}\) mass concentrations < 35 \(\mu\)g·m\(^{-3}\)), good (35 \(\mu\)g·m\(^{-3}\) < PM\(_{2.5}\) mass concentrations < 75 \(\mu\)g·m\(^{-3}\)), acceptable (75 \(\mu\)g·m\(^{-3}\) < PM\(_{2.5}\) mass concentrations < 115 \(\mu\)g·m\(^{-3}\)), poor (115 \(\mu\)g·m\(^{-3}\) < PM\(_{2.5}\) mass concentrations < 150 \(\mu\)g·m\(^{-3}\)), and bad (PM\(_{2.5}\) mass concentrations > 150 \(\mu\)g·m\(^{-3}\)).

Wuhan experienced a severe pollution event from 18 January to 21 January, during which the hourly average mass concentration of PM\(_{2.5}\) was 170 \(\mu\)g·m\(^{-3}\), which was 1.9 times the overall average in January.

According to Figure 2, the value of PM\(_{2.5}\) mass concentration was moderately low, with an average of 58.9 \(\mu\)g·m\(^{-3}\) before 8:00 on 14 January. Excellent and good days were observed during this period. Both the visibility and RH were relatively high, and average values of 7.4 km and 68.9% were observed, respectively. The temperature was as low as 2.8 °C. The mean wind speed was 1.3 m·s\(^{-1}\) on average, and the maximum was 4.1 m·s\(^{-1}\). The mean values of light scattering components (OC, NO\(_2\), and water-soluble ions) and light absorbent components (EC) were 91.5 \(\mu\)g·m\(^{-3}\) and 2.7 \(\mu\)g·m\(^{-3}\) respectively.
From 8:00 on 14 January to 16:00 on 18 January, both acceptable and poor days were observed, and the average concentration value of PM$_{2.5}$ was 109.0 $\mu$g·m$^{-3}$. During this period, the temperature was low, and there was a high RH, presenting mean values of 5.3 °C and 84.9%, respectively. The mean value of wind speed remained unchanged at 1.3 m·s$^{-1}$, while the maximum reached 5.1 m·s$^{-1}$. The mean concentration values of light scattering components and light absorbent components increased, with mean values of 108.5 $\mu$g·m$^{-3}$ and 4.3 $\mu$g·m$^{-3}$, respectively, resulting in a decrease in visibility to 2.5 km.

The mean value of PM$_{2.5}$ mass concentration increased rapidly to 170.0 $\mu$g·m$^{-3}$ from 16:00 on 18 January to 15:00 on 21 January. Wuhan experienced a severe pollution event composed of bad days during this period, which was related to unfavorable climate conditions such as low wind speed and high RH. On one hand, the wind speed reduced to 0.8 m·s$^{-1}$, which is not conducive to the horizontal and vertical diffusion of PM$_{2.5}$. On the other hand, the average RH reached as high as 91.7%, which was approximately 1.3 times higher than the first period. Increasing RH facilitates the aerosol hygroscopic growth and further enhances the aerosol liquid water, facilitating the secondary aerosols formation by serving as an important medium for liquid-phase and heterogeneous reactions [26]. Therefore, high RH will increase PM$_{2.5}$ concentrations and worsen pollution. The temperature increased to 6.1 °C. Finally, the sum of the concentrations of light scattering components and light absorbent components reached as high as 124.3 $\mu$g·m$^{-3}$, leading to a quick reduction of visibility, with an average of 1 km.

After this severe pollution event, due to the impact of precipitation and high wind speed (3.3 m·s$^{-1}$), the air quality improved rapidly with an average PM$_{2.5}$ mass concentration of 66.0 $\mu$g·m$^{-3}$. The average value of temperature decreased to 1.1 °C as a result of evaporative cooling by precipitation. RH decreased slightly to 89.4%. The mean values of light scattering components and light absorbent components reduced to the same range as seen in the first period. The visibility increased to 3.0 km.
3.2. Optical Properties under Different Pollution Levels

3.2.1. Diurnal Variations of Optical Parameters on Clean and Polluted Days

Clean days (PM$_{2.5}$ mass concentrations < 75 µg·m$^{-3}$) and polluted days (PM$_{2.5}$ mass concentrations > 75 µg·m$^{-3}$) were defined in order to analyze the influence of meteorological elements on optical properties under different pollution conditions. According to Figure 3, $b_{abs}$ peaked at 9:00 on clean days, while it did not vary much on polluted days. $b_{ext}$ had an identical diurnal variation to that of $b_{scat}$ on both clean and polluted days. $b_{ext}$ presented a unimodal distribution that peaked at 19:00 on polluted days and it was pretty flat on clean days. Clear unimodal diurnal patterns of $b_{ext}$ might be related to the evolution of the planetary boundary layer (PBL) and daily pollution emission trends. Since from the sunset, the height of the PBL decreased, and the turbulent mixing weakened due to the decrease of temperature. Therefore, PM$_{2.5}$ accumulated in the lower atmosphere. In addition, emission from vehicles and factories increased in the evening rush hour, which led to high concentrations of PM$_{2.5}$. High PM$_{2.5}$ concentrations led to the increase of $b_{ext}$, which peaked at 19:00. As time passed and temperature increased, the turbulent mixing was enhanced, and the height of the PBL increased, leading to the decrease of PM$_{2.5}$ concentration and $b_{ext}$ values during the daytime. Besides, $b_{abs}$ was pretty low than $b_{abs}$ on polluted days in the early morning hours, indicating that more absorbent particles appeared in the morning.

![Figure 3](image-url)

Figure 3. Diurnal variations of $b_{abs}$, $b_{scat}$, $b_{ext}$, wind speed, relative humidity (RH), and PM$_{2.5}$ on clean and polluted days.
The diurnal variation of optical parameters on polluted days was quite different from that on clean days. As shown in Figure 3, the values of $b_{abs}$, $b_{scat}$, and $b_{ext}$ on polluted days were higher than those on clean days because the concentration of PM$_{2.5}$ was higher on polluted days, which means there will be more particles in the atmosphere absorbing and scattering light. Furthermore, according to Figure 3c, $b_{ext}$ increased rapidly starting at 12:00 and peaked at 19:00, with a value of 818.1 Mm$^{-1}$ on polluted days. The value of $b_{ext}$ did not change much during the day on clean days. The peak of $b_{ext}$ on polluted days was related to meteorological conditions. According to Figure 3, the wind speed decreased significantly starting at 6:00 and continuously decreased from 2.2 m s$^{-1}$ to 1.0 m s$^{-1}$ over the next 6 h. Therefore, PM$_{2.5}$ began to accumulate due to the low wind speeds, leading to a significant increase in PM$_{2.5}$ concentration at 12:00. RH began increasing at 8:00 and reached 95% at 17:00, after which it remained almost unchanged. With high RH, aerosol liquid water not only augments particle sizes, which enhances aerosol scattering, but also substantially enhances secondary aerosol formation. Therefore, these two factors together led to the rapid increase of PM$_{2.5}$ concentrations at 12:00.

3.2.2. Analysis of Optical Parameters under Different Pollution Levels

According to Figure 4, PM$_{2.5}$ mass concentrations increased with pollution levels. The average mass concentrations of PM$_{2.5}$ were 25.95 $\mu$g m$^{-3}$, 56.53 $\mu$g m$^{-3}$, 93.83 $\mu$g m$^{-3}$, 130.9 $\mu$g m$^{-3}$, and 168.43 $\mu$g m$^{-3}$ on excellent, good, acceptable, poor, and bad days, respectively. The high levels of PM$_{2.5}$ led to a rapid increase of $b_{ext}$, the value of which was 854.72 Mm$^{-1}$ on bad days, which was 4.86, 3.1, 2.29, and 1.28 times that on excellent, good, acceptable, and poor days, respectively. The value of $b_{scat}$ was 816.36 Mm$^{-1}$ on bad days and was 4.98, 3.19, 2.19, and 1.29 times that on excellent, good, acceptable, and poor days, respectively. The value of $b_{abs}$ was 31.72 Mm$^{-1}$ on acceptable days, which was 1.6 times that on good days. However, as pollution levels continued to increase, the value of $b_{abs}$ did not change substantially and was 38.74 Mm$^{-1}$ and 38.36 Mm$^{-1}$ on poor and bad days, respectively.

![Figure 4.](image-url)

Figure 4. Evolution of the average values of $b_{abs}$, $b_{scat}$, $b_{ext}$, PM$_{2.5}$, and single scattering albedo (SSA) under different pollution levels.

The single scattering albedo (SSA) is the ratio between the aerosol scattering coefficient and the aerosol extinction coefficient, reflecting the relative importance of aerosol scattering and absorption, and it is an important factor affecting global climate change. As shown in Figure 4, the value of SSA varied from 91.5% to 95.5%. The minimum value appeared on acceptable days, indicating an enhancement of absorption ability. SSA value increased with pollution levels on polluted days (including acceptable, poor, and bad days) and reached a maximum of 95.5% on bad days, showing that the contribution of scattering to light extinction was greater for higher pollution levels on polluted days.
RH is an important factor affecting the optical properties of PM$_{2.5}$. RH was divided into five sections: 20–60%, 60–80%, 80–90%, 90–95% and 95–100%, in order to analyze the effect of RH on optical properties. According to Figure 5, $b_{\text{scat}}$ showed a similar trend as $b_{\text{abs}}$. The values of $b_{\text{abs}}$ and $b_{\text{ext}}$ at the same RH range value increased with pollution levels. The growth rate of $b_{\text{scat}}$ and $b_{\text{ext}}$ grew with increasing pollution levels. In addition, $b_{\text{scat}}$ and $b_{\text{ext}}$ under all pollution levels increased with the increase of RH when RH was less than 95%. Many components of atmospheric aerosols are hygroscopic, meaning that they take up water as RH increases, and the sizes and effective radius of particles will be augmented, therefore, aerosol light scattering and extinction will be enhanced [26]. However, $b_{\text{scat}}$ and $b_{\text{ext}}$ began to decrease when RH exceeded 95%.

The $b_{\text{abs}}$ showed a clear relationship with RH only on excellent and good days (Figure 4b). On excellent and good days, $b_{\text{abs}}$ decreased with the increase of RH when RH was less than 90% but grew with the increase of RH when RH was more than 90%. The values of SSA under all pollution levels were low when RH was less than 80%, which means the contribution of scattering to light extinction was low (Figure 4d). The maximum of SSA on excellent and good days appeared at the RH range value of 80–90%, while the maximum on acceptable and poor days appeared at 95–100%.

3.2.3. Contribution of PM$_{2.5}$ Chemical Components to Light Extinction under Different Pollution Levels

The values of $b_{\text{ext}}$ and contributions of aerosol chemical components to $b_{\text{ext}}$ were calculated in order to determine the effect of chemical components on visibility impairment (Figure 6). During the entire study period, the average value of $b_{\text{ext}}$ was 366.8 Mm$^{-1}$, and NH$_4$NO$_3$ was the largest contributor to $b_{\text{ext}}$, accounting for 25.2%, followed by OM (20.1%), coarse mass (19.4%), (NH$_4$)$_2$SO$_4$ (15.1%), and soil made the smallest contribution, accounting for only 1.1%.

![Image](image-url)
According to Figure 6a, the value of $b_{ext}$ increased with the level of pollution. The value of $b_{ext}$ was 854.7 Mm$^{-1}$ on bad days and was 4.9 and 2.3 times that on excellent days and overall, respectively. In addition, the contribution rate of each chemical component to $b_{ext}$ changed as the pollution level increased. OM was the largest contributor to $b_{ext}$ on excellent days, accounting for 22.1%, and NH$_4$NO$_3$ and (NH$_4$)$_2$SO$_4$ accounted for 16.7% and 12.8%, respectively. The contribution of NH$_4$NO$_3$ and (NH$_4$)$_2$SO$_4$ to $b_{ext}$ increased with pollution level. NH$_4$NO$_3$ contributed the most to $b_{ext}$ on poor days, accounting for 42.1%. It was followed by (NH$_4$)$_2$SO$_4$, which accounted for 20.7%. The contribution of OM decreased to 12.5%. The contribution of NH$_4$NO$_3$ to $b_{ext}$ decreased slightly from poor days to bad days, but it was still the largest contributor. NH$_4$NO$_3$ was the largest contributor to $b_{ext}$ on bad days, accounting for 38.2%, followed by (NH$_4$)$_2$SO$_4$ (27.0%), and the contribution of OM to $b_{ext}$ decreased to 10.9%. EC, sea salt, soil, coarse mass, NO$_2$, and Rayleigh made a minor contribution, together accounting for 23.9%.

NH$_4$NO$_3$ and (NH$_4$)$_2$SO$_4$ were the major components of light extinction in Wuhan, indicating that NH$_4$NO$_3$ and (NH$_4$)$_2$SO$_4$ played an important role in visibility impairment. The other chemical components, such as OM, EC, sea salt, coarse mass, and so on, were not the major factors affecting visibility on polluted days since their contribution decreased significantly on poor and bad days.

### 4. Conclusions

The optical properties of PM$_{2.5}$ and the influence of meteorological parameters under different pollution levels were studied in Wuhan in January 2018. Wuhan experienced a severe pollution event from 18 January to 21 January, during which time the average concentration value of PM$_{2.5}$ was 170 µg m$^{-3}$, which was 1.9 times the overall average in January. $b_{ext}$ showed a unimodal distribution on polluted days, peaking at 19:00. $b_{ext}$ was larger on polluted days than on clean days for the whole day. $b_{ext}$ on clean days did not change much during the day. On polluted days, $b_{ext}$ increased significantly starting at 12:00 and occurred along with adverse meteorological factors, including a decrease in wind speed and an increase in RH. The value of $b_{ext}$ increased with pollution level and was 854.72 Mm$^{-1}$ on bad days, which was 4.86, 3.1, 2.29, and 1.28 times that on excellent, good, acceptable, and poor days, respectively. The value of SSA varied from 91.5% to 95.5%, increasing with pollution levels on polluted days. $b_{ext}$ and $b_{ext}$ under all pollution levels increased with RH when RH was less than 95%. When RH exceeded 95%, $b_{ext}$ and $b_{ext}$ began to decrease on acceptable, poor, and bad days, but they still increased on excellent and good days. NH$_4$NO$_3$ was the largest contributor to overall $b_{ext}$, accounting for 25.2%, followed by OM (20.1%), while the contribution of soil was the lowest, accounting only for 1.1%. It is apparent that the contribution of (NH$_4$)$_2$SO$_4$ and NH$_4$NO$_3$ to $b_{ext}$ was much higher with increasing pollution levels. NH$_4$NO$_3$ contributed the most to $b_{ext}$ on bad days, accounting for 38.2%, followed by (NH$_4$)$_2$SO$_4$ (27.0%), and the contribution of OM to $b_{ext}$ reduced to 10.9%.

Figure 6. Variation of $b_{ext}$ and relative contributions of each species to $b_{ext}$ under different pollution levels.
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