Dew condensation during a typical haze event in Changchun, China

Yingying Xu, Zhaoqing Luan and Hui Zhu

ABSTRACT

Haze is one of the most serious environmental problems affecting China. This study monitored the changes in dew amount and quality during a haze event that occurred in 2016. Water vapor migrated continuously to the near surface during the haze event. The period of dew condensation increased because of meteorological factors, and the daily dew amount (0.178 mm) was higher during the haze event than in non-haze weather (0.0607 mm). The concentrations of all ions in the dew increased gradually during the haze event, peaking during the most serious period of the haze. The concentrations of SO$_4^{2-}$ and NH$_4^+$ reached 15,325.95 and 13,865.45 μeq/L, which were 2.24 and 10.83 times greater than those obtained before the haze event, respectively. During the haze event, the particulate matter (PM) concentrations within the dew increased, and the mass concentrations of PM$_{2.5}$ and PM$_{2.5-10}$ during the worst haze event were 65.3 and 166.1 mg/L, respectively. The dew mainly removed coarse PM; the average removal rates of PM$_{2.5}$ and PM$_{2.5-10}$ during the haze event were 13.6% and 16.9%, respectively. Dew can capture PM throughout a haze event, and its purifying effect on the underlying surface was obvious, especially during the beginning of the event.

Key words | chemical characterization, dew, haze, particulate matter, removal ability

INTRODUCTION

Dew condensation is a common weather phenomenon, and dew is a crucial input for the water balance of the surface layer. Therefore, dew has attracted considerable interest, and extensive studies have identified dew amounts, chemical characteristics, and effect factors in the local water balance of desert (Agama & Berliner 2006), selva (tropical rain forest) (Liu et al. 2005), meadow (Clus et al. 2008), and wetland environments (Xu et al. 2012). Dew condensation is an effective natural purification process (Rubio et al. 2012). Particulate matter (PM) can be captured as condensation nuclei as dew condenses, whereas gases or liquid particles might dissolve into dewdrops (Galek et al. 2015). Thus, the chemical composition in dew is closely related to atmospheric precipitation (Takeuchi et al. 2002; Polkowska et al. 2008).

Motor vehicle exhaust emissions, industrial waste gases, and coal combustion have increased the level of urban air pollution in China (Chen et al. 2017). Consequently, haze occurs frequently with high concentrations of PM, high relative humidity (RH), and a temperature inversion (Pan et al. 2016; Gao et al. 2017). Air quality decreases during such hazy weather. Some studies found that the mass concentrations of PM$_{2.5}$ and PM$_{10}$ during haze are 4–6 times higher than non-haze days (Sun et al. 2006), and the concentrations of nearly all water-soluble ions (NH$_4^+$, Mg$^{2+}$, Ca$^{2+}$, K$^+$, Na$^+$, Cl$^-$, NO$_3^-$, F$^-$, and SO$_4^{2-}$) increase during a haze event (Wang et al. 2006; Tan et al. 2009). Airborne PM sedimentation is related to wet deposition (rain or dew) and dry sedimentation processes (gravity settling), and the wet deposition process is the main pathway (Lekouch et al. 2011).
Rain can remove PM and gases from the atmosphere efficiently (Hu et al. 2005). Dew condensation is concentrated within the 0–3 m layer above the ground surface (Muskała et al. 2015; Ernesto & Jasson 2016), and humans are sensitive to near-surface airborne PM, such as PM$_{2.5}$ and PM$_{10}$ (Tang et al. 2017). The particles can be removed by the dew condensation process, and dew is known to condense during haze days (Xu et al. 2017). But dew collection is difficult, and thus near-surface PM removal by dew is rarely reported. Consequently, the amount of PM that can be removed by dew during haze periods remains unknown. Furthermore, some meteorological factors, such as RH, temperature, and wind speed, change markedly during haze events (Pan et al. 2016), and these factors can all affect dew condensation. But few reports exist on how dew intensity or dew water quality changes in relation to the particle concentrations, RH, or visibility near the surface.

The contribution of dew to the removal of near-surface airborne PMs can be determined by studying the changes in the chemical composition of dew during hazy weather. The objectives of the present study were to analyze the intensity and chemical characteristics of dew during a haze event, identify the ability of dew to remove atmospheric PM during haze days, and reveal the effects of haze on dew condensation. The results may improve the understanding of the role of dew in scavenging airborne pollutants and provide important information related to the mechanisms and pathways of airborne pollutant removal during hazy weather.

**EXPERIMENTS**

**Sampling site and process of haze event**

Dew samples were collected at Jilin Jianzhu University, in the southeastern part of the city of Changchun in Jilin Province, China. Jilin Jianzhu University is located in the middle of the city center and suburbs, and it can easily collect the dew water. This site is affected by residential, traffic, and construction emissions that are representative of Changchun. Therefore, it can be a representative place. The population density of Changchun is approximately 1,000 people km$^{-2}$, and heavy traffic is a problem. Generally, 132–136 dew days occur annually, which account for 62.5% of the frost-free season in Changchun (Xu et al. 2017). Under the synergy of meteorological conditions caused by the burning of corn, straw, or fossil fuels, such as coal, combined with seasonal temperature inversions, Changchun frequently experiences haze events in autumn.

The studied haze event began at 20:00 local time (LT) on November 3, 2016. The visibility decreased from 10 km, and the air quality gradually deteriorated. The air condition became heavily polluted at 10:00 LT on November 5 and persisted until 16:00 LT on November 6, after which the haze gradually disappeared. The haze did not disappear fully until 16:00 LT on November 8, 2016. Dew samples were collected at 4 h intervals from 00:00 LT on November 3 until 24:00 LT on November 8, 2016. Thus, 36 dew samples were collected during this event.

**Meteorological data**

Meteorological data, including air temperature (°C), dew point (°C), RH (%), wind speed (m·s$^{-1}$) at 1-m height, and water vapor pressure (hPa), were gathered at hourly intervals during the condensation period using the Milos 520 automatic weather station (Vaisala, Finland) in Jilin Jianzhu University. Visibility and PM (PM$_{2.5}$ and PM$_{10}$) data in Changchun were collated from http://www.wunderground.com and http://www.pm25.in/changchun, respectively.

**Dew sample collection and analysis**

**Dew intensity monitoring**

Dew was monitored *in situ*. Poplar wood sticks were selected as the monitor. These sticks were polished and cut into 18 cm × 3.5 cm × 3.5 cm (length × width × height) pieces. An observation shelf with three layers was set up near the weather station. The layer included a bottom layer (5 cm above the ground surface), a middle layer (1.5 m above the ground surface), and a top layer (3 m above the ground surface). The monitors were weighed at the beginning of the haze event (20:00 LT on November 3, 2016) and collected and weighed at 4 h intervals until the end of the haze (16:00 LT on November 8, 2016) with an electronic balance (accuracy: ±0.001 g). The
actual dew per unit area was computed as the average of the three heights.

Sample collection and analysis

Dew samples collected using different collection surfaces can vary substantially (Chiwa et al. 2003); however, polytetrafluoroethylene (PTFE) has been proven a proper surface for dew collection (Rubio et al. 2008). In this study, dew water was collected in pre-cleaned 250 mL PTFE bottles. The PTFE bottles were placed within the green belt along a campus road (approximately 1.0 m above the ground level). It should be noted that it is difficult to distinguish between the coagulation and sedimentation processes, and the particles collected include two parts, the gravity settling part and the dew condensation nuclei. Major soluble cations (Ca^{2+}, Mg^{2+}, Na^+, K^+, and NH_4^+) and anions (F^-, Cl^-, NO_3^-, and SO_4^{2-}) were analyzed using an ion chromatograph (LC-20AD; Shimadzu, Japan).

Particle diameter analysis

The particle diameters in dew were measured using a JL-1166 Laser Particle Analyzer (Chengdu Jingxin Powder Analysis Instrument Co., Ltd., Chengdu, Sichuan, China). All collected dew samples were analyzed to determine the total dissolved solids, PM_{2.5} (PM < 2.5 \mu m in diameter), and PM_{2.5-10} (PM 2.5–10 \mu m in diameter), with the subtraction method. The first step is to determine the dew volume and dilute to 450 mL, followed by shaking and dividing the dilution into three parts. The three samples were filtered through pre-weighed 10-, 2.5-, or 0.22-\mu m membrane filters, respectively, which were then dried for 12 h. Then, the filters were weighed again and the total dissolved solids, PM_{2.5}, and PM_{2.5-10} of the dew were calculated from the difference. The last step is to calculate the PM_{2.5} and PM_{2.5-10} concentration in dew with the weight and the real volume (150 mL divided by the enrichment factor).

Data analysis

Statistical analyses were conducted using the SPSS software version 16.0 (IBM Corp., NY, USA). The equations of particle removal efficiency by dew are as follows:

\[ R_i = \frac{Q_i^{\text{dew}}}{Q_i^{\text{air}}} \times 100\% \]  

(1)

where \( i \) is the type of PM (\( i = 1 \) represents PM_{2.5}, and \( i = 2 \) represents PM_{2.5-10}). \( R \) is the particle removal efficiency by dew, \( Q_i^{\text{dew}} \) and \( Q_i^{\text{air}} \) are the weights of particles in the dew and air (mg), respectively.

\[ Q_i^{\text{dew}} = \frac{I \times C_i \times V}{3} \]  

(2)

where \( I \) is the dew intensity (mm), \( C_i \) is the concentration of particles in the dew (mg/L), \( V \) is the air inflow during dew condensation (m^3), and \( 3 \) is the hypothesized dew condensation concentrated at 0–3 m above the ground surface.

\[ I = \frac{10 \times (W_e - W_b)}{S} \]  

(3)

where \( W_b \) and \( W_e \) are the weights of each monitor at the beginning and end of the intervals in the different layers (g), respectively; \( S \) is the surface area of the monitor (cm^2); and 10 is the conversion factor.

\[ Q_i^{\text{air}} = W_{f\text{e}} - W_{f\text{b}} \]  

(4)

where \( W_{f\text{b}} \) and \( W_{f\text{e}} \) are the weights of the filter at the beginning and ending of the intervals (g).

RESULTS AND DISCUSSION

Dew intensity

According to the monitoring results obtained from 2014 to 2015, dew intensity is correlated positively with RH and air temperature (\( n = 254, P < 0.01 \)) and correlated negatively with PM_{2.5}, PM_{10}, and nocturnal wind speed (\( n = 254, P < 0.01 \)) (Xu et al. 2017). However, during a haze period, dew intensity is correlated positively with RH (\( n = 36, P < 0.01 \)), correlated negatively with air temperature and visibility (\( n = 36, P < 0.01 \)), and has no
relationship with PM$_{2.5}$, PM$_{2.5-10}$, and wind speed ($n = 36$, $P > 0.05$) (Table 1). By analyzing the correlation coefficients between dew intensity and meteorological factors during the haze (Figure 1), dew intensity also appeared to be significantly positively correlated with RH ($n = 36$, $P < 0.01$), negatively correlated with temperature and visibility ($n = 36$, $P < 0.01$), and with no relationship with wind speed ($n = 36$, $P > 0.05$). It does not conform to the usual rule.

Using the two-year data, we found that dew intensity correlates positively with air temperature. The reason is that rain and heat occur during the same period in Changchun. Moisture is abundant in air at high temperatures during summer and autumn (July–September). Moreover, surface water vapor is prone to condense. When airborne PM concentration is low after rain, dew condensation considerably increases. This study revealed that dew intensity is negatively correlated with temperature because of the short monitoring period and because the near-surface meteorological conditions of a ‘warm and wet inversion’ are beneficial to water vapor condensation. Furthermore, during the haze event, wind speed was generally low and had no substantial change. Thus, no relationship was found between dew condensation and wind speed, and RH is the most important factor affecting dew condensation in both haze and non-haze weathers. Dew intensity was correlated negatively with visibility because low visibility corresponds to high RH during periods of haze.

Table 1 | Correlation coefficients between dew intensity and meteorological factors in haze

<table>
<thead>
<tr>
<th></th>
<th>PM$_{2.5}$</th>
<th>PM$_{2.5-10}$</th>
<th>Temperature</th>
<th>RH</th>
<th>Wind speed</th>
<th>Visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dew intensity</td>
<td>0.239</td>
<td>0.213</td>
<td>-0.468**</td>
<td>0.922**</td>
<td>-0.056</td>
<td>-0.628**</td>
</tr>
</tbody>
</table>

The analysis period is 00:00 LT on November 3 until 24:00 LT on November 8, 2016.

**Correlation is significant at the 0.01 level. *Correlation is significant at the 0.05 level.

Figure 1 shows that dew formed under haze weather conditions; therefore, haze weather conditions do not influence dew condensation. The usual period of dew condensation is from half an hour after sunset to half an hour before sunrise. However, according to the results of the
experiment, dew condensation has no relationship with sunrise and sunset times under haze weather conditions. When haze occurs, the dew condensation period does not adhere to the norm; instead, it lasts for as long as the haze event persists.

The daily amounts of dew recorded in this study on November 3–8 were 0.075, 0.129, 0.202, 0.175, 0.207, and 0.177 mm. The high RH in the atmosphere was conducive to dew condensation in severe haze (Figure 2). The average daily dew intensity in the study area was 0.178 mm on haze days and 0.0607 mm during non-haze weather (Xu et al. 2011). In an urban ecosystem, Ye et al. (2010) found that the highest mean dew amounts were observed in forest areas (0.034 mm night$^{-1}$), followed by industrial (0.022 mm night$^{-1}$), commercial (0.013 mm night$^{-1}$), and residential (0.009 mm night$^{-1}$) areas. In another study, the dew amount was found to be 0.11–0.13 mm in the grassy area and 0.07–0.09 mm in the urban center of Vancouver, BC (Richards 2002). These amounts are all lower than the amount obtained in our research area during the haze event. The reason is that daily average condensation time is typically 10 h but this increases to 24 h during haze. Thus, under haze weather conditions, the near-surface meteorological conditions are beneficial to water vapor condensation, which can extend the condensation period. This can lead to increased amounts of condensation and abnormally high daily amounts of dew.

**Ionic composition of dew**

Dew chemical characterization has been reported in other areas. In the humid regions of an urban ecological system, the differences in dew water quality are obvious. As shown in Table 2, the ion concentration in the dew of the study area is significantly higher than the ion concentrations in Poland and the United States. This result may be attributed to the fact that the study area is an industrial city, in which factory and car exhaust emissions are relatively concentrated and coal combustion is a serious problem in winter. The mean ionic compositions of dew in haze and non-haze weathers are shown in Table 2. Overall, NH$_4^+$ and SO$_4^{2-}$ were the most abundant cation and anion. The decreasing order of ionic concentration in dew in haze weather was SO$_4^{2-}$ > NH$_4^+$ > Ca$^{2+}$ > NO$_3^-$ > K$^+$ > Cl$^-$ > F$^-$ > Na$^+$ > Mg$^{2+}$ and SO$_4^{2-}$ > NH$_4^+$ > Ca$^{2+}$ > NO$_3^-$ > Na$^+$ > Cl$^-$ > F$^-$ > K$^+$ > Mg$^{2+}$ in non-haze weather. The concentration of all ions in dew increased on hazy days. The concentrations of various ions were much higher on hazy days than on non-hazy days, that is, 2.24–10.83 times greater. Heating by coal combustion and straw burning is
the main cause of haze in Changchun. From the fire map on November 2 (Figure 3), it can be seen that there were nearly 70 fire points located in the north of the experiment plot, and that indicated the straw was burned at these points. The wind direction was mainly from the north during the haze event. Specifically, K⁺ is derived from biomass burning, and large amounts of straw are burned in and around Changchun in November. This is the reason for the largest variation of K⁺ among the water-soluble ions throughout the sampling period.

As shown in Figure 4, the concentrations of all ions in dew increased as the haze event developed, peaking when the haze was at its worst. The SO₄²⁻ and NH₄⁺ concentrations reached 15,325.95 and 13,865.45 μeq/L, respectively, which are 5.87 (SO₄²⁻) and 4.40 (NH₄⁺) times greater than normal. After the haze subsided, the concentrations of the ions decreased slowly, and the dew quality returned to levels similar to those before the haze event. Under haze weather conditions, the atmospheric PM increased and the air quality decreased. The mass concentrations of PM₂.₅ and PM₂.₅-₁₀ were 4–6 times higher during periods with haze than on non-hazy days (Sun et al. 2015), and the concentrations of almost all water-soluble ions (NH₄⁺, Mg²⁺, Ca²⁺, K⁺, Na⁺, Cl⁻, NO₃⁻, F⁻, and SO₄²⁻) increased during the haze event (Wang et al. 2006; Tan et al. 2009). The ion concentrations in dew and air particles also have synchronous patterns. Thus, dew is an important indicator of environmental air quality because it can reflect atmospheric pollution conditions.

**Particulate matter**

During the haze period, the concentration of PM in the dew increased, but its removal rate decreased. As shown in Figure 5, the mass concentration of PM₂.₅ rose from 12.7 mg/L to 65.3 mg/L and that of PM₂.₅-₁₀ rose from

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**Table 2** Main ion composition of dew (μeq/L) in Changchun and other reported cities

<table>
<thead>
<tr>
<th>Ion</th>
<th>Changchun, China (This study)</th>
<th>Xu et al. (2015) (non-haze)</th>
<th>Wroclaw, Poland (Galek et al. 2011)</th>
<th>Argonne, USA (Wesely et al. 1990)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg²⁺</td>
<td>187.7</td>
<td>55.8</td>
<td>20</td>
<td>–</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>2,489.8</td>
<td>796.3</td>
<td>108</td>
<td>–</td>
</tr>
<tr>
<td>Na⁺</td>
<td>251.5</td>
<td>112.3</td>
<td>16</td>
<td>230.4</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>6,760.7</td>
<td>1,536.9</td>
<td>40</td>
<td>6.67</td>
</tr>
<tr>
<td>K⁺</td>
<td>680.2</td>
<td>62.8</td>
<td>–</td>
<td>148.7</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>1,265.0</td>
<td>169.2</td>
<td>115</td>
<td>50.8</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>9,295.3</td>
<td>1,584.5</td>
<td>45</td>
<td>204.2</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>353.6</td>
<td>105.6</td>
<td>56</td>
<td>183.1</td>
</tr>
<tr>
<td>F⁻</td>
<td>316.7</td>
<td>85.6</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

**Figure 3** Fire points around the experiment plot on November 2, 2016.
33.3 mg/L to 166.1 mg/L at the start of the haze event (04:00 LT on November 3) until the worst haze condition (08:00 LT on November 6). At the end of the haze event at 24:00 LT on November 8, the mass concentrations of PM$_{2.5}$ and PM$_{2.5-10}$ decreased to 13.0 and 39.5 mg/L, respectively. For the same time references above, the removal rate of PM$_{2.5}$ decreased from 22% to 10.5% and then increased to 18.2%. Meanwhile, the removal rate of PM$_{2.5-10}$ decreased from 27% to 12.6% and then increased to 24.6%. The removal rate of PM$_{2.5-10}$ was always higher than that of PM$_{2.5}$, and the condensation nuclei of dew were mainly based on the coarse particles. During the period of haze, the average removal rate of PM$_{2.5-10}$ was 16.9%, while that of PM$_{2.5}$ was 13.6% (from 20:00 LT on November 3 to 16:00 LT on November 8). The concentration of particulates in the dew was significantly higher

![Figure 4](image)

Figure 4 | Ionic concentrations of NH$_4^+$, Mg$^{2+}$, Ca$^{2+}$, K$^+$, Na$^+$, Cl$^-$, NO$_3^-$, F$^-$, and SO$_4^{2-}$ of dew from 00:00 LT on November 3 to 24:00 LT on November 8, 2016 in Changchun (interval: 4 h).

![Figure 5](image)

Figure 5 | (a) Removal efficiency of PM$_{2.5}$ and PM$_{2.5-10}$ by dew and (b) PM$_{2.5}$ and PM$_{2.5-10}$ concentrations in dew from 00:00 LT on November 3 to 24:00 LT on November 8, 2016 in Changchun (interval: 4 h).
in the haze, while the PM also rose significantly in the atmosphere. During hazy weather, the particles in the atmosphere are not easily settled or dispersed. This can lead to slow water vapor condensation, thereby causing the significant drop in the removal rate of particulates in the dew.

CONCLUSIONS

To understand the dew condensation during a haze period, we monitored dew in a haze event that occurred in November 2016 in Changchun. We found that vapor condensed near the surface throughout the entire process. The dew intensity during haze was closely related to RH ($P < 0.01$), negatively correlated with temperature ($P < 0.01$), and had no relationship with wind speed and PM ($P > 0.05$). The period of condensation was increased during haze, and thus the daily amount of dew in haze was higher than in non-haze weather. Through the analysis of dew water, we established that the concentrations of all ions increased during the haze event, peaking at the time when the haze was at its worst. As the haze subsided, the concentrations of the ions decreased slowly, and the water quality of the dew returned to a level similar to that before the haze occurred. Therefore, the water quality of dew reflects the changes in airborne particles. Dew water mainly removed coarse PM (PM$_{2.5-10}$), while the concentration of PM increased with the development of the haze event, and its rate of removal by dew decreased.

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