Accumulation and Coarse Modes Particle Concentrations during Dew Formation and Precipitation

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Abstract

This study investigates the number concentrations of accumulation mode (0.3–1 µm) and coarse mode (1–10 µm) particles in the eastern Mediterranean urban environment with and without precipitation and dew formation. The results show that the number concentrations of both the accumulation mode and coarse mode particles decreased (ratio ~0.7 and ~0.36, respectively) during precipitation. In the analysis we assumed that dew formation occurs in Amman during nighttime when the relative humidity (RH) was higher than 80% and the difference between the temperature and dew point temperature (i.e. T – DP) was less than 2.5 °C. In general, the accumulation mode particle number concentration increased with increasing relative humidity. On average, the accumulation mode particle number concentration doubled during the dew formation. On the contrary, the coarse mode particle number concentration during the dew formation was 30% less than that during no dew formation. The increased number concentration of accumulation mode particles during the dew formation conditions is most likely due to enhanced water vapor condensation on existing ultrafine aerosols (diameter < 0.1 µm) enabling their growth to detectable sizes reaching the accumulation mode particle size. The decreased number concentration of coarse mode particles during the dew formation could be due to enhanced wet deposition.

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1. Introduction

Aerosol number concentration is affected by aerosol sources and favorable meteorological conditions (e.g. Munir et al., 2017; Liu et al., 2016; Aromolo et al., 2015; Dimitriou, 2015; Wang et al., 2015; Li et al., 2012; Mølgaard et al., 2012; Cheng and Li, 2010; Hussein et al., 2006; Hosiokangas et al., 2004; Charron and Harrison, 2003; Harrison et al., 2001; Nicholson, 1993). Various removal processes play a role determining the number concentrations (e.g. Seinfeld and Pandis, 2006). These removal processes (e.g. wet deposition) are a very well-known mechanisms. Dew and fog formation are other processes related to water vapor condensation that might affect and interact with atmospheric aerosols (e.g. Boris et al., 2018; Nath and Yadav et al., 2018; Yang et al., 2018; Kaul et al., 2014; Yadav and Kumar, 2014; Singh et al., 2011). While wet deposition due to precipitation is evident, the effect of dew formation on atmospheric aerosols has not been yet evaluated sufficiently to be understood.

The wet deposition is divided into in-cloud and below-cloud scavenging processes (Chate, 2005; Seinfeld and Pandis, 2006). Cloud droplets can encapsulate aerosols in-clouds that efficiently remove fine aerosols with high solubility (Chang et al., 1987; Seinfeld and Pandis, 2006). It is believed that below-cloud scavenging, which is an aerosol washout process by precipitation, is an efficient removal process for coarse mode aerosols (Bae et al., 2012). In general, below-cloud scavenging is mainly affected by rain droplet size distributions, terminal velocity of the rain droplets, precipitation intensity and aerosols size distributions (Scott, 1982; Levine and Schwartz, 1982).

Dew is a phenomenon that involves water vapor condensation on a substrate such as environmental surfaces (Beysens 1995). Water vapor can also condense on an airborne particle, which plays a role as a condensation nuclei (CN) forming fog (Beysens 1995). During dew formation, a phase
transition occurs when the water vapor phase transforms into a liquid phase on a substrate, which is held at a lower temperature of the water vapor phase. This is sometimes considered as an alternative source of water in semi-arid areas, where the harvested dew water amount might exceed that collected from rainfall (Agam and Berliner 2006).

In general, dew is formed via two main steps: (1) nucleation of a liquid phase forming a droplet on an obstacle (particle, surface, etc.) and (2) growth of the droplet due to condensation of water at the expense of the surrounding atmosphere (Beysens 1995). As later postulated by Beysens (2006a), the presence of a substrate that geometrically constrains the growth is the origin of the peculiarities and richness of the phenomenon. A key point is the droplet interaction through droplet fusion or coalescence, which leads to scaling in the growth and gives universality to the dew formation process. During the first step of dew formation, heterogeneous nucleation of vapor (such as condensation of water vapor onto CN) is more efficient than homogeneous nucleation. During the second step of dew formation, the migration of vapor molecules from the atmosphere onto the formed droplet is a very complicated process.

As a practical manifestation, most of the attention about dew formation is given to the amount harvested or even to the quality of harvested dew water to be potable water or utilized in for other applications, especially in semi-arid areas (Odeh et al. 2017; Galek et al. 2015 and 2012; Vuollekoski et al. 2015; Lekouch et al. 2011 and 2010; Polkowska et al. 2008; Beysens et al. 2007 and 2006b; Muselli et al. 2006; Okochi et al. 2005; Shachak et al. 2002; Jiries 2001; Alnaser and Barakat 2000; Zangvil 1996). To our knowledge, the effect of dew formation on accumulation mode and coarse mode aerosol concentration has not been considered in real-life conditions in semi-arid areas.

In this study, the accumulation mode and coarse mode aerosol particle number concentrations were investigated with respect to precipitation and probability of dew formation. The analysis was based on long-term measurement of particle number concentration (optical diameter 0.3–10 µm) and
ambient conditions such as relative humidity, dew point, ambient temperature, and precipitation determined in Amman, Jordan.

2. Materials and methods

2.1. Aerosol particle number size distributions

The particle number size distributions (optical diameter 0.3–10 µm) were measured with an Optical Particle Sizer (OPS, TSI model 3330) during February 2013 – July 2017. The OPS was operated with “TSI default” setting that included 13 size-bins of equally lognormal width within the measured optical particle diameter range; i.e. 0.3, 0.316, 0.422, 0.562, 0.75, 1, 1.334, 1.778, 2.371, 3.162, 4.217, 5.623, 7.499, and 10 µm. According to the manufacturer, the size resolution < 5% at 0.5 µm and concentration range 0 – 3000 cm⁻³. The instrument was routinely checked for zero count (background) and inlet flow was regularly measured with a primary calibrator (TSI, 4146).

The measurement location was at the Department of Physics, the University of Jordan. The aerosol inlet was channeled through the window of a laboratory on the second floor (height from the ground was about 10 meters). Local meteorological conditions and particularly wind fields can affect the observed aerosol concentrations when the sampling is made from the side of a building (e.g. Dos Santos-Juusela et al., 2013; von Bismarch-Osten et al., 2013; Pirjola et al., 2012; Vardoulakis et al., 2003).

The aerosols sampling was as close as possible beneath the weather station operated at the roof of the building. It should be kept in mind that it was not possible to setup OPS on the top of the building (being at the same height of the weather station) due to harsh weather conditions (high temperature and intense solar radiation almost every day) in Jordan that might damage the OPS or even alter its operation.

The sampling time-resolution of the OPS was set to 5 minutes while the sample flow rate was kept at 1 liter per minute (L min⁻¹). A diffusion drier was set up to the sample flow prior to the OPS. The
penetration efficiency through the tubing and the diffusion drier was determined experimentally and the raw aerosol data-set was corrected accordingly.

The campus of the University of Jordan is located in the northern part of Amman, Jordan. It is about 10 km from the city center. The campus is surrounded by a residential area with small roads network. In the vicinity, the main source of air pollution is traffic emissions in addition to local-scale residential heating in the winter. The traffic source is composed of a mixture of personal cars operating on gasoline engine and heavy duty and low duty transport (mini bus and pickups), which are mainly equipped with diesel engines. The gasoline used in Jordan is unleaded fuel 90 and 95 octane whereas the diesel is not a high grade and it has high content of sulfur (e.g. Hamdi et al., 2008). The residential heating utilizes household kerosene and natural gas heaters in addition to central heating operating on diesel. Furthermore, natural air pollution is also a problem in Jordan mainly in form of episodic sand dust storms in the spring and local dust resuspension, which is dominant in the autumn. (e.g. Hussein et al., 2018).

2.2. Weather conditions

The weather parameters were measured on the roof top of the Department of Physics since February 2015. The measurements were conducted with a commercial weather station (Weather Station WH-1080, Clas Ohlson: Art.no. 36-3242). The time resolution of the measurements were 5 minutes. The station measured temperature (-40–65 °C, resolution 0.1 °C), pressure (918.7–1079.9 hPa, resolution 0.3 hPa), humidity (10%–99%, resolution 1%), wind speed (1–160 km h⁻¹) and wind direction (16 sectors), and rain (0–9999 mm, resolution 0.3 mm below 1000 mm and 1 mm over 1000 mm).

The data logger program (Easy Weather, version 7.3) provided additional weather parameters: dew point, gust, absolute and relative pressure, wind chill, and precipitation during different time periods (hourly, 24 hours, weekly, monthly, and accumulated).

2.3. Data handling
The aerosol data-base was corrected for sampling losses. The aerosol and the weather data-bases were quality checked. The hourly averages were calculated for the data-bases and then used in further analysis. The particle number concentrations were calculated for two size fractions: accumulation mode (diameter 0.3–1 µm) and coarse mode (diameter 1–10 µm). This was simply done by integrating the measured particle number size distribution over the specified particle diameter range.

2.4. Air mass back trajectories

Air mass history was investigated by calculating air parcel backtrajectories using HYSPLIT model (Draxler and Hess, 1997; Draxler et al., 2012; Stein et al., 2015) to follow the origin and path of air masses that arrived at the measurement site. Two-days back trajectories were calculated for each hour at arrival heights 100, 500, and 1500 meters. The results for different arrival heights were similar; and therefore in the subsequent analysis we considered the results for 100 meters arrival height only.

3. Results and Discussion

First we explore the aerosol removal process by precipitation by comparing observed aerosol number concentrations before the precipitation events and during rain. Then we study the effect of dew formation on aerosol number concentrations during nighttime.

3.1. Aerosols removal by precipitation

As a starting point, the rainy days from the observation data were selected based on the precipitation measurement whenever the 24-hour precipitation exceeded 10 mm (Fig. 1) during that period of time. Since the precipitation events in Amman occur usually during the winter the analysis was applied for that period; i.e. November through February. In total there were 38 rain days and
141 days without rain, with corresponding aerosol and weather data were during the measurement period.

Overall, during the precipitation days, the number concentrations of both the accumulation mode and coarse mode particles are lower than what could be observed during days without rain (Fig. 2). The ratio between the average number concentrations during the rainy days and the days without rain was about 0.76 and 0.36 for the accumulation mode particles and coarse mode particles, correspondingly. This reduction in the number concentration in both of the particle size-fractions is clearly affected by wet deposition (Seinfeld and Pandis, 2006).

The decrease in the accumulation mode and coarse mode particle concentrations due to precipitation was previously reported e.g. by Li et al. (2016), who showed that the effect of rain scavenging is related to the rain intensity and duration in addition to the wind speed and direction. According to their observations, the rainfall was most efficient at removing particles with diameter \( \sim 0.6 \, \mu m \) and greater than \( 3.5 \, \mu m \). In another study by Rathnayake et al. (2017), the authors showed that bioaerosol concentrations (such as pollens, fungal spores, and Gram-negative bacterial endotoxins) were efficiently reduced during the rain events.

Nicolas et al. (2009) reported similar results during rain events for coarse mode particles concentration, which were reduced. However, they showed that the number concentration of accumulation mode particles increased during rain events. They explained that coarse mode particles cleansing is effective with moderate precipitation.

Castro et al. (2010) showed that the rain events with intensities over \( 3.2 \pm 1.5 \, mm \, h^{-1} \) decreased the number concentration of both small and large particles. Their result was in agreement with that reported by Nicolas et al. (2009) for rain intensity < \( 0.6 \, mm \, h^{-1} \), when a considerable increase in the concentration of aerosols with diameter < \( 1.3 \, \mu m \) whereas those with diameter > \( 1.3 \, \mu m \) their concentrations decreased. Castro et al. (2010) explained that during very weak rain intensity the measurement probe might not discriminate adequately between aerosols and small precipitating droplets or the extremely small droplets that remain in suspension in the atmosphere and therefore
misinterpreted as aerosol particles. As a consequence, data from very weak rain events (with an intensity of less than 0.6 mm h\textsuperscript{-1}), such as drizzle or dense fog, should be treated separately. In fact, this was also noticed here and taken into consideration.

Looking at the 48-hours air mass back trajectories footprints (Fig 3), the trajectories were spatially covering longer distance during rain hours than those during hours without rain. Furthermore, during rain hours, the majority of trajectories originated from the Black Sea, West Turkey, and East Greece and crossing over the Eastern Mediterranean (Fig 3(a)). These type of trajectories are typically characterized as humid and have a high probability of rainfall, which washes out particulate matter from the atmosphere. During hours without rain, the majority of trajectories originated from North Saudi Arabia, West Iraq, and nearby the shorelines in the Eastern Mediterranean (Fig 3(b)). These types of trajectories explain the dry weather conditions and less probability of rainfall during these periods of time. Furthermore, the differences in the air mass origin affects the aerosols characteristics in accordance with the source type and strength as well as time-spent over continental versus marine regions. As such, North Saudi Arabia and West Iraq are well-known regions for sand dust, which increase the potential of high concentrations in the coarse and to some extent the accumulation mode particles. On the other hand, trajectories originated over marine regions do not have potential to accompany high concentrations in the coarse mode particles.

### 3.2. Aerosol concentration during dew formation

During dew formation days (based on observation during March, April, and June 2015 (Table 1); Odeh et al. 2017), the median value of the relative humidity was 85\% (average: 82.7 ± 9.9) and the median value of the difference between the temperature and the dew point (i.e. T – DP) was about 2.3 \textdegree C (average: 3.0 ± 2.0); see also Table 2. The results shown in Table 2 are based on 5-minutes time-resolution of the weather conditions for those hours when the dew formation was reported. Furthermore, these dew formation events were observed during the nighttime only. Therefore, it can be assumed that dew formation in Amman occurs during nighttime (starts before midnight and ends
before sunshine) with the condition RH > 80% and T – DP < 2.5 °C and an additional condition precipitation = 0 mm/h. The additional condition to account for the precipitation was considered in order to separate the effects of the precipitation from that of the dew formation. Therefore it was assumed that the dew formation will not occur (i.e. T – DP > 5 °C) and it does not coincide with RH > 80%. In a previous work by Gandhidasan et al. (2018), the collected amount of fog water harvested was significantly enhanced when the relative humidity was over 80%.

Our results show that the number concentration of the accumulation mode increased with increasing relative humidity regardless to the difference between the temperature and the dew point (Fig. 4(a)). The average value of the accumulation mode particle number concentration was about 37 cm$^{-3}$ during relative humidity range 10–20% whereas it was about 96 cm$^{-3}$ during relative humidity range 90–100%. On average, the ratio of the accumulation mode particle number concentration during dew formation and without the dew is nearly double. Similar results were reported for the accumulation mode particles during cloud and fog formation in the urban atmosphere (e.g. Che et al., 2015).

However, the number concentration of the coarse mode particles showed a different trend (Fig. 4(b)). During the condition of no dew formation (i.e. T – DP > 5 °C), the coarse mode particle number concentration was rather constant at about 2 cm$^{-3}$ as long as the relative humidity was below 50%. Overall, the coarse mode number concentration were very low and typical concentrations varied between 1.5 cm$^{-3}$ to 3 cm$^{-3}$. When looking these concentrations together with the dew formation, however, the coarse mode particle number concentration behaved in a different manner than the accumulation mode. The coarse mode number concentration jumped to about 3 cm$^{-3}$ when the relative humidity was in the range 50–60% but decreased to about 2 cm$^{-3}$ within relative humidity 70–80%. During favored dew formation conditions (i.e. T – DP < 2.5 °C and relative humidity > 80%), the coarse mode particle number concentration continued to decrease and reached a value of approximately 1.5 cm$^{-3}$. Therefore, on average, the ratio of coarse mode particle number concentration ratio during and without dew was about 0.7. Takeuchi et al. (2003) showed that dew...
water dominantly associated with the coarse mode particles rather than fine particles. Indirectly this indicates that the coarse mode particle scavenging might be more important for the coarse mode particle than for the accumulation mode particles during the dew formation.

We performed air mass back trajectory analysis in a similar manner for both the dew formation hours and hours without the dew formation (Fig 5). During both cases, similar footprint areas were identified. The trajectories were originated from the Eastern Mediterranean, specifically from the Aegean Sea. However, they were shorter and slower the during dew formation hours than those during hours without dew formation. In a sense, the aerosol sources for both cases were similar to each other, but their residence times were different.

The results show that the increased number concentration of the accumulation mode particles during dew formation conditions is likely due to enhanced water vapor condensation onto existing aerosols. They might have higher content of nitrates and sulfates as their transport to the observation site was slower over the Eastern Mediterranean being exposed to high emissions of anthropogenic emissions from the ships as well as industrial and traffic activities in the region. For example, the Jordanian diesel has high content of sulfur (e.g. Hamdi et al., 2008). The longer exposure times for these emissions might have transformed them into more hygroscopic while accumulating inorganic material during their transport to the site. At the same time, the slowly moving air masses over the Eastern Mediterranean also gave aerosols more time to coagulate and accumulate mass, possibly through heterogeneous chemistry, coinciding the low number concentrations of the accumulation mode particles with conditions of the dew formation.

The decreased number concentration of coarse mode during the dew formation conditions can be due to several reasons. As a first glance, clean air masses can have a direct influence; but this is not likely the case because during clean air masses the concentrations of all particle size fractions are decreased. Another more probable reason is enhanced vapor condensation on the coarse mode particles leading them to grow and reach even larger sizes and elevated deposition. Indeed, this phenomenon of micron particle scavenging needs further investigations with more extensive
measurement campaigns as well as in chambers, where the environmental conditions are well
constrained. For example, Xu et al. (2015) reported that the dew has the ability to capture
particulate matter and act as a removal process for micron particles.

We recall here that sampling from the side of a building might affect the aerosols observation (e.g.
Dos Santos-Juusela et al., 2013; von Bismarch-Osten et al., 2013; Pirjola et al., 2012; Vardoulakis
et al., 2003). For example, Vardoulakis et al. (2003) reported there are interactions between the
winds above the street canyon and the secondary circulation within the street canyon leading to
spatial variability in the aerosol concentration. They also point out that during calm winds (< 1.5 m
s⁻¹), the differences are not pronounced. Furthermore, Pirjola et al. (2012) determined aerosol
number concentrations on both sides of the road in the urban street canyon. During their
measurements the wind speed was 5 m s⁻¹ at the rooftop perpendicular to the street canyon. In
these conditions, the number concentration in the leeward side were up to a factor of 4 higher due to
secondary circulation. Therefore, our observations are influenced by these local meteorological
features but due to single observation site, their detailed effects cannot be addressed in more detail.

4. Conclusion

This study is focused on the number concentrations of accumulation mode and coarse mode
particles during precipitation and dew formation and we compared their differences during
conditions with and without rain or with and without dew formation. The analysis was based on
hourly processed weather data-base (temperature, dew point, relative humidity, and precipitation)
and particle number size distribution data-base (optical diameter 0.3–10 µm). The number
concentrations of accumulation mode particles (0.3–1 µm) and coarse mode particles (1–10 µm)
was derived by integrating the measured particle number size distribution over the specified
diameter range.

The results show that the number concentrations of both the accumulation mode and coarse mode
particles were lower during precipitation in comparison to the conditions than were observed during
days without rain. The concentration ratios between the number concentration during rainy days to those during days without rain was ~0.76 and ~0.36; respectively for accumulation mode and coarse mode particles, indicating strong scavenging by precipitation. The accumulation mode particle number concentration increased with increasing relative humidity regardless to the difference between the temperature and the dew point \((T – DP)\). On average, the accumulation mode particle number concentration was two times higher during the nights with the dew formation than that without. The coarse mode particle number concentration during dew formation was about a factor of 0.7 in contrast to the conditions of no dew formation. Most likely, the increased number concentration of accumulation mode particles during dew formation conditions was due to enhanced water vapor condensation on existing ultrafine aerosol particles \((\text{diameter} < 0.1 \, \mu\text{m})\), which might have grown to accumulation mode particle size in these conditions. The decreased number concentration of coarse mode particles during the dew formation could be due to enhanced vapor condensation on the coarse mode particles that they grow reaching droplet sizes and removed rapidly from the atmosphere due to wet deposition. It seems feasible that the aerosols can act as efficient condensation nuclei \((\text{CN})\) for water vapor nearby the Earth’s surface and remove it onto environmental surfaces as dew droplets. This phenomenon might be enhanced to initiate dew formation by seeding aerosols close to the surface and thereby increase liquid water accumulation e.g. for agriculture.

ACKNOWLEDGMENTS

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Table 2: Statistical analysis for the relative humidity and the difference between the temperature and the dew point during observed dew formation event (reported by Odeh et al. 2017).
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<table>
<thead>
<tr>
<th>Start Date (before midnight)</th>
<th>End Date (before sunshine)</th>
<th>Dew Volume Collected [mm]</th>
<th>Mean T [°C]</th>
<th>Mean DP [°C]</th>
<th>Mean RH [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2</td>
<td>March 3</td>
<td>130</td>
<td>7.2 ± 0.2</td>
<td>5.7 ± 0.4</td>
<td>90 ± 2</td>
</tr>
<tr>
<td>March 3</td>
<td>March 4</td>
<td>130</td>
<td>6.8 ± 0.2</td>
<td>5.1 ± 0.3</td>
<td>89 ± 3</td>
</tr>
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<td>April 1</td>
<td>April 2</td>
<td>130</td>
<td>9.8 ± 0.9</td>
<td>7.0 ± 0.7</td>
<td>82 ± 8</td>
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<tr>
<td>April 3</td>
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<td>70</td>
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<td>8.1 ± 0.3</td>
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<tr>
<td>April 13</td>
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<tr>
<td>June 14</td>
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<td>June 20</td>
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<td>15.4 ± 0.9</td>
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<td>17.2 ± 1.2</td>
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<td>19.6 ± 1.1</td>
<td>10.6 ± 0.5</td>
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Table 2: Statistical analysis for the relative humidity and the difference between the temperature and the dew point (i.e. T – DP) during observed dew formation event (reported by Odeh et al. 2017).

<table>
<thead>
<tr>
<th></th>
<th>mean ± std</th>
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<th>5%</th>
<th>25%</th>
<th>Median</th>
<th>75%</th>
<th>95%</th>
<th>Max</th>
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<td>77.0</td>
<td>85.0</td>
<td>89.5</td>
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<td>T – DP [°C]</td>
<td>3.0 ± 2.0</td>
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<td>0.8</td>
<td>1.7</td>
<td>2.3</td>
<td>4.0</td>
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<td>9.9</td>
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Figure 1: Daily averages of the number concentrations for (a) accumulation mode particles and (b) coarse mode particles. On each plot the 24-hour precipitation condition during the winter time (November, December, January, and February) is marked with red-circle for precipitation = 0 and blue-square for precipitation > 10 mm.

Figure 2: Statistical plot for the number concentration of (a) accumulation mode particles and (b) coarse mode particles with respect to the precipitation conditions during the winter time (November, December, January, and February); days with 24-hour precipitation > 10 mm are indicated as “Rain” and those without 24-hour precipitation are indicated as “no Rain”.

Figure 3: Footprint of air mass back trajectories during (a) rain hours and (b) hours without rain.

Figure 4: Number concentration of (a) accumulation mode particles and (b) coarse mode particles versus relative humidity for both cases: when the temperature and dew point difference is larger than 5 °C (i.e. not favoring dew formation) and it is less than 2.5 °C (i.e. favoring dew formation).

Figure 5: Footprint of air mass back trajectories during (a) dew formation hours and (b) hours without dew formation.
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Figure 4: Number concentration of (a and c) accumulation mode particles and (b and d) coarse mode particles versus relative humidity (RH) and “Temperature – Dew Point” (T – DP) for both cases: when the temperature and dew point difference is larger than 5 °C (i.e. not favoring dew formation) and it is less than 2.5 °C (i.e. favoring dew formation).
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