

Impact of Misting Systems on Local Particulate Matter (PM) Levels

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ABSTRACT

In hot, arid environments, many outdoor spaces are cooled by misting systems. These systems spray a fine mist of water droplets that cool down the surrounding air through the endothermic evaporation process. As water sources often contain dissolved minerals, the evaporating droplet may leave an airborne particulate matter (PM) residue. Currently there is no information available on the impact of misting systems on localized PM concentrations. In this study, PM concentrations are found to increase by a factor of 8 from ambient levels in the vicinity of a residential misting system in controlled experiments. These experiments show PM concentrations decrease with increasing distance from misting systems. Chemical data reveal that chloride and magnesium ions may be used locally as tracers of particles from misting systems as chloride may be subject to atmospheric transformation. The average chloride concentration was $71 \mu\text{g m}^{-3}$ in samples collected while the misting system was operational and below the detection limit ($< 8.2 \mu\text{g m}^{-3}$) in samples collected when the misting system was off. The average magnesium concentration was $11.7 \mu\text{g m}^{-3}$ in samples when misting system was on and $0.23 \mu\text{g m}^{-3}$ in samples when misting system was off. Ambient measurements of PM_{10} in public places cooled by misting ranged from $102 \pm 10 \mu\text{g m}^{-3}$ to $1470 \pm 150 \mu\text{g m}^{-3}$, and $\text{PM}_{2.5}$ ranged from $95 \pm 10 \mu\text{g m}^{-3}$ to $990 \pm 100 \mu\text{g m}^{-3}$. Calculations suggest that misting systems could potentially emit PM quantities on the order of a gram per hour in the respirable particle size range.

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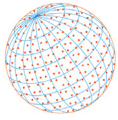
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1 INTRODUCTION

Particulate matter (PM) refers to microscopic solid and liquid particles that are suspended in air, consisting generally of organic matter, soot, metals, acids, soil, and dust (Seinfeld and Pandis, 2016). The sizes of suspended particles range from ~ 0.002 – $100 \mu\text{m}$ in diameter, but larger particles ($> 10 \mu\text{m}$ diameter) fall out of suspension faster than smaller particles due to the influence of gravity (Fowler *et al.*, 2009; Eagar *et al.*, 2017). A common classification is PM_{10} and $\text{PM}_{2.5}$, referring to particles with diameters $\leq 10 \mu\text{m}$ and $\leq 2.5 \mu\text{m}$, respectively (Anderson *et al.*, 2012). Particles greater than $2.5 \mu\text{m}$ in diameter may be inhaled and deposited in the tracheobronchial region; this region is covered with a layer of mucus, where the particles are deposited and then removed from the body by the motion of cilia (Finlayson-Pitts and Pitts, 1999). Fine particles, those less than $2.5 \mu\text{m}$ in diameter, can be inhaled by the lungs and reach the alveoli, where gas exchange with the blood takes place and where there is no mucus or cilia (Phalen, 2009). Components of fine particles may enter the bloodstream, and furthermore, the residence time of these particles in the body is much greater than that of larger particles that are deposited on mucus in the tracheobronchial region (Schlesinger, 1988).

PM is known to have an impact on human health, with the link between chronic exposure to increased PM concentrations and increased mortality rate demonstrated extensively (Dockery *et al.*, 1993; Samet *et al.*, 2000). Brook *et al.* (2010) showed that increased PM concentrations are



related to cardiovascular disease, reporting that for any increase in overall mortality caused by PM, two thirds of the deaths could be attributed to cardiovascular disease. The respiratory system is affected by pulmonary oxidative stress and inflammation when individuals are acutely exposed to increased PM concentrations (Anderson *et al.*, 2012). High PM concentrations may also cause neurodegenerative disorders, although these relationships are less well understood (Campbell, 2004).

The United States has implemented regulations on PM₁₀ and PM_{2.5} to limit exposure to citizens. The National Ambient Air Quality Standards (NAAQS) established by the Environmental Protection Agency (EPA), state that the average level of PM₁₀ over a 24-hour period must be less than 150 $\mu\text{g m}^{-3}$, and PM_{2.5} must be less than 35 $\mu\text{g m}^{-3}$ (U.S. EPA, 1990). The Occupational Health and Safety Administration also defines exposure limits of 15 mg m^{-3} total suspended particulates (TSP) and 5 mg m^{-3} respirable particulates (U.S. Department of Labor, 2014). Respirable particulates refer to the mass fraction of particles that can reach the alveoli, the median value of which is 4.25 μm and generally considered to represent PM₁₀ (Connelly and Jackson, 2013). These are based on averages over an 8-hour period, and are known as permissible exposure limits (PELs).

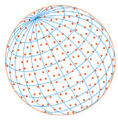
Ambient misting systems may pose an uninvestigated source of PM. While industrial sources have used spray devices to impact and collect PM (Pollock and Organiscak, 2007), ambient misting systems use fine droplet streams released into the ambient air in hot, arid locations to cool down outdoor spaces. Mistifiers cool down the surrounding air by the endothermic evaporation of the water droplets they emit. When the droplets evaporate, PM may be formed from the residual of dissolved material in the water used for misting. The use of misting systems is thus hypothesized to increase the concentration of PM in the surrounding air. This study investigates the impact of misting systems on local air quality by measuring particle concentrations in a controlled experiment while a misting system is periodically operated, and by measuring PM concentrations in public places with mistifiers in operation. Ion analysis using ion chromatography (IC) is used to characterize air samples taken throughout the controlled experiment and compared with major ion concentrations in the water used to generate the mist. Finally, engineering calculations are used to estimate the quantity and size of PM potentially generated by misting system operation.

2 METHODS

2.1 Sampling

Particle concentrations and ambient/misting PM samples were obtained during controlled experiments conducted on the back patio of a house in Scottsdale, AZ. An Orbit 12' Portable Mist Cooling Kit (Orbit Irrigation Products, North Salt Lake, UT, USA) was installed on the roof of the house and connected to the house water supply. A DustTrak DRX Aerosol Monitor 8533 (TSI, Shoreview, MN, USA) was used to measure particle concentrations (total suspended particulate matter TSP, particulate matter with aerodynamic diameter less than 10 μm (PM₁₀), less than 2.5 μm (PM_{2.5}) and less than 1 μm (PM₁)) throughout the controlled experiments. Measurements to determine compliance with regulatory standards have specific requirements for equilibration to minimize artifacts from water sorption which were not possible with this measurement approach. As a result, there may be bias between these measurements and regulatory standard levels. The misting system was turned on and off over 1 hour intervals to obtain and compare particle concentrations from periods when the misting system was operating (hereafter called misting periods) and periods when the misting system was not operating (hereafter called ambient periods). The distance between the aerosol monitor and the wall where the mistifiers were installed was varied between different trials of the experiment to analyze the effect of distance on particle concentration. An Aircheck Sampler Model 224-PCXR8 (SKC Inc. Eighty Four, PA, USA) was used to collect PM samples from ambient and misting periods. The average flow rate of these samples was controlled at 3.7 L min^{-1} with sampling periods ranging from 40–60 minutes; one misting sample was taken over three hours. Samples of airborne PM were collected on 47 mm polytetrafluoroethylene filters (Pall Corporation, Port Washington, NY, USA) placed in an open-faced filter holder. A total of 19 PM filter samples were collected and analyzed. Three water samples were collected from the outdoor faucet in pre-cleaned plastic bottles.

Measurements of airborne PM concentrations were also obtained from public places where



misting systems were in operation using the DustTrak DRX 8533. Data were collected from four locations in Tempe, AZ with outdoor misting systems, herein referred to as Locations 1, 2, 3, and 4. At all locations, the DustTrak was placed in the near vicinity of the misters in a location where an individual would be sitting or walking. After about 5–10 minutes, the DustTrak was moved to a more remote location away from the misting system, such as on the sidewalk outside the patio of a restaurant.

All measurements were made in summertime Arizona when outside temperatures were higher than 90 F (often 100F and higher) and relative humidity was less than 25% (dew ranges are stated). Under these conditions, aqueous mist droplets of ~50 μm evaporate within a few seconds (Niimura and Hasegawa, 2019). As a consequence the PM size cuts by the DustTrak are likely to represent dry particles, considering the travel time and distance to the measurement device although some residual wetness cannot be excluded.

2.2 Sample Preparation

For analysis by ion chromatography, filters were placed face down in a plastic cup and immersed in ultrapure water ($> 18.3 \text{ M}\Omega \text{ cm}$) and ethanol (reagent grade, Fisher Scientific, Waltham, MA, USA), 7.5 mL and 100 μL , respectively. The plastic cup was sealed and sonicated for 15 minutes, after which the mixture was transferred to a plastic vial using a plastic syringe. The mixture was dispensed through a pre-wet 0.22 μm Millex-GP polyethersulfone (PES) membrane syringe filter (Millipore, Burlington, MA, USA). Water samples were prepared by passing 7.5 mL of the sample through a syringe filter. Each water sample was diluted 5x with ultrapure water. Both the diluted and original samples were analyzed.

2.3 Ion Chromatography

Measurement of ionic species was performed using a Dionex IC20 Ion Chromatograph (Dionex, Sunnyvale, CA, USA) equipped with Dionex AS50 Autosampler. For anion analysis, a Dionex IonPac AS12A analytical column ($4 \times 200 \text{ mm}$) was used in series with a Dionex IonPac AG12A guard column ($4 \times 50 \text{ mm}$). For cation analysis, a Dionex IonPac CS12A analytical column ($4 \times 250 \text{ mm}$) was used in series with a Dionex IonPac CG12A guard column ($4 \times 50 \text{ mm}$). Anions were eluted with a mobile phase consisting of 2.7 mM sodium carbonate/0.3 mM sodium bicarbonate and cations were eluted with a mobile phase consisting of 20 mM methanesulfonic acid. The chromatographic experiment was performed at a flow rate of 1.00 mL min^{-1} and the sample volume used was 20 μL .

Standard solutions were prepared by dilution of a stock solution prepared from analytical grade reagents. The most concentrated anion standard contained fluoride (22 mg L^{-1}), bromide (106 mg L^{-1}), chloride (32 mg L^{-1}), sulfate (150 mg L^{-1}), nitrite (102 mg L^{-1}), nitrate (50.1 mg L^{-1}), and phosphate (148 mg L^{-1}). The most concentrated cation standard contained lithium (49.8 mg L^{-1}), sodium (205 mg L^{-1}), ammonium (246 mg L^{-1}), potassium (487 mg L^{-1}), magnesium (250 mg L^{-1}), and calcium (500 mg L^{-1}). Both the cation and anion stock standards were diluted with ultrapure water in series following the ratios 4:5, 3:5, 1:5, 1:10, 1:16.67, 1:25, 1:50, 1:100, and 1:600 (sample:total volume) to make a total of 10 standards including the stock.

3 RESULTS AND DISCUSSION

3.1 Impact of Misting Systems on PM Concentrations

Fig. 1 shows a timeline of DustTrak data during a trial of the controlled experiment conducted on September 18, 2018 where the average TSP increased by a factor of 14 between periods of the misting system operating (misting) and not operating (ambient). A similar plot can be generated from each trial of the controlled experiments, where average TSP concentrations consistently increase by a factor of 8.

Fig. 2 shows a plot of the percent change of the different size classes of particles. Three size classes were considered, $\text{PM}_{2.5}$, coarse particles $\text{PM}_{2.5-10}$ (particles with aerodynamic diameter between 2.5 and 10 μm), and $\text{PM}_{>10}$ (particles with diameter $> 10 \mu\text{m}$). As shown in Fig. 2, the size class responsible for the increase in particle concentration is $\text{PM}_{2.5-10}$. However, on other experimental days, $\text{PM}_{2.5}$ was responsible for the increase in particle concentration between misting and ambient periods.

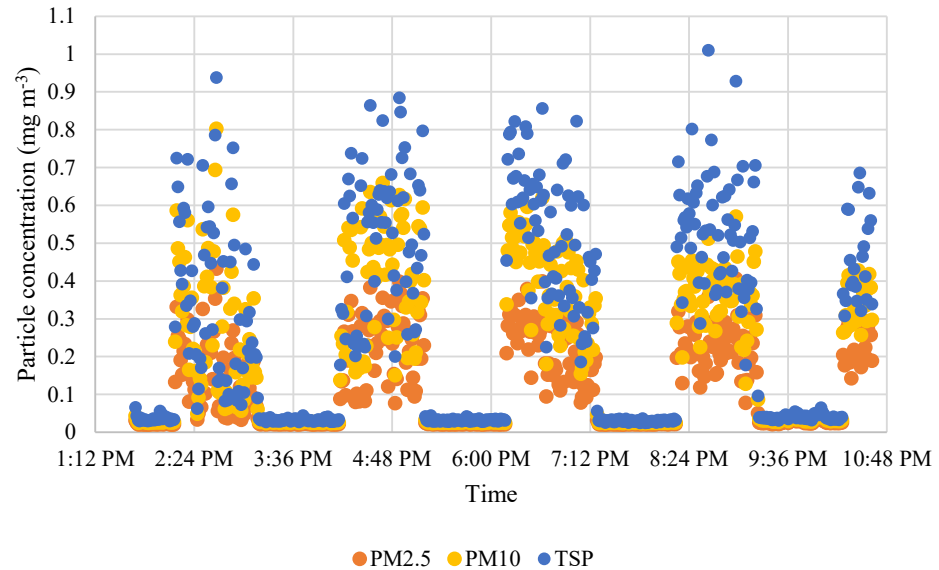
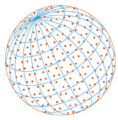


Fig. 1. Particle concentration vs. time plotted for a trial of the controlled experiment conducted on September 18, 2018 where the dew point ranged from 50–64°F.

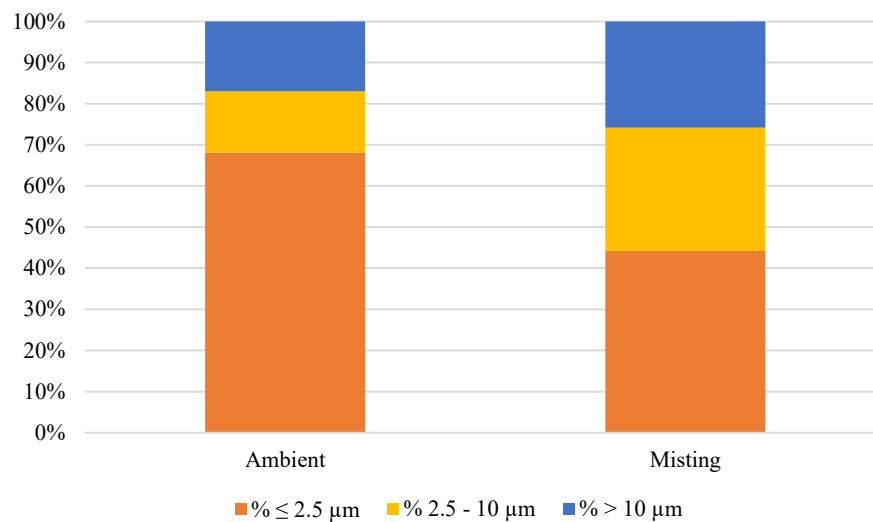


Fig. 2. Percent change of the size classes PM_{2.5}, PM_{2.5-10}, and particles > 10 μm in diameter between misting and ambient periods measured on September 18, 2018 where the dew point ranged from 50–64°F.

In all trials of the controlled experiment, PM concentrations increased significantly when misting systems were operating. The ambient PM levels measured during misting do not exceed the NAAQS concentrations or OSHA PELs, even considering that some residual wetness might be present; however, the controlled experiment showed that PM concentrations increase in the immediate vicinity of misting systems which still can pose a significant health risk to individuals. For example, data from Fig. 1 show that the total average particle concentration during the ambient periods was 34 μg m⁻³, which increased to 475 μg m⁻³ during misting periods, representing an increase in PM levels by a factor of 14. Overall, concentrations increased by factor range of 4–14, with the average factor of increase being 8.

3.2 Impact of Misting Systems on PM Concentrations in Public Places

Fig. 3 shows a timeline of DustTrak data collected from Location 2 which indicates increased particle concentrations in public places. Measured PM is elevated near operating misting systems

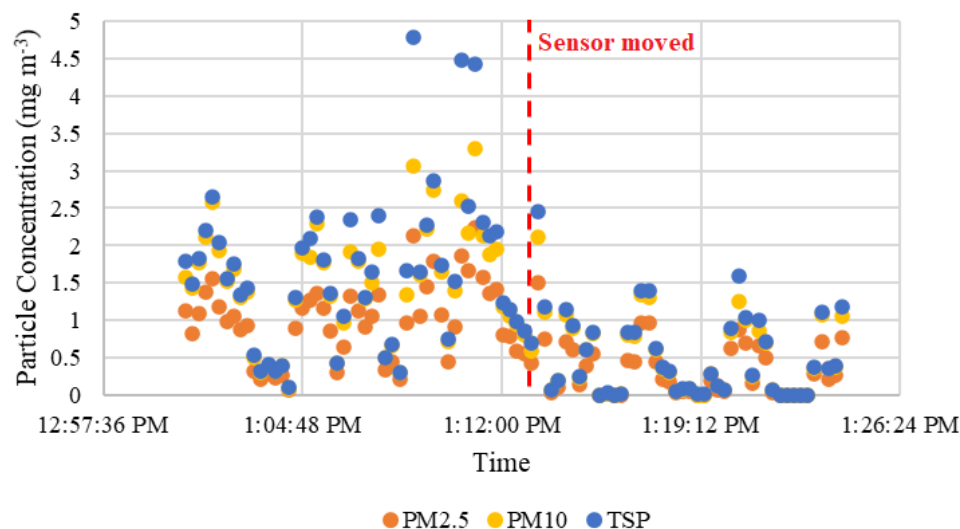
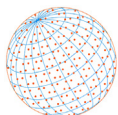


Fig. 3. Particle concentration vs. time at location 2. The DustTrak was deployed on a table on the patio for about 13 minutes. After 13 minutes (indicated by the vertical line labeled on the graph), the DustTrak was carried out to the sidewalk next to the restaurant. The dew point ranged from 44–63°F.

Table 1. Average PM₁₀ and PM_{2.5} of public locations.*

Location	PM ₁₀ ($\mu\text{g m}^{-3}$)	PM _{2.5} ($\mu\text{g m}^{-3}$)
1	102	95
2	1470	991
3	337	256
4	454	322

*All measurements were taken on the same day where the dew point ranged from 44–63°F.

with measured PM three times greater near misting systems compared to locations further removed from misting systems. The latter can be the result from dilution as well as residual evaporation. Table 1 shows the average PM₁₀ and PM_{2.5} for locations in the immediate vicinity of operating misting systems in all four public places. The PM₁₀ and PM_{2.5} concentrations of Locations 2, 3, and 4 are higher than the NAAQS values for PM₁₀ and PM_{2.5}, but they do not violate these standards because they are not based on 24-hour averages and might contain some residual wetness. While PM concentrations may not violate NAAQS standards, this does not mean they are benign and without associated health risks. None of the average TSP or PM_{2.5} concentrations recorded at public places violate OSHA standards.

The majority of the measured PM₁₀ mass is characterized as PM_{2.5}. On average for the four locations, the PM_{2.5} mass constitutes 77% of the PM₁₀ mass. PM_{2.5} has a higher potential to cause health effects, due to its higher residence time in the atmosphere and its ability to penetrate deep within the lungs (Schlesinger, 1988). For comparison, in Fig. 4 the PM_{2.5} concentrations from locations 1–4 were plotted against PM_{2.5} concentrations from other locations where heavy aerosol concentrations exist. These include an urban street canyon in The Hague, Netherlands (Boogaard *et al.*, 2011), patios of bars where second hand smoke exists (Kaplan, *et al.*, 2019), Beijing (Quan *et al.*, 2014), and Los Angeles (Chow *et al.*, 1994).

3.3 PM Concentrations Decrease with Increasing Distance from Misting Systems

Trials of the controlled experiment were conducted in which the distance of the DustTraks to the roof mounted misting system was varied; trials were performed with the horizontal distance between the misting and the DustTrak varying between 6 to 11 feet. Fig. 5 shows the data from these experiments. While there is significant uncertainty in the PM measurement, there does

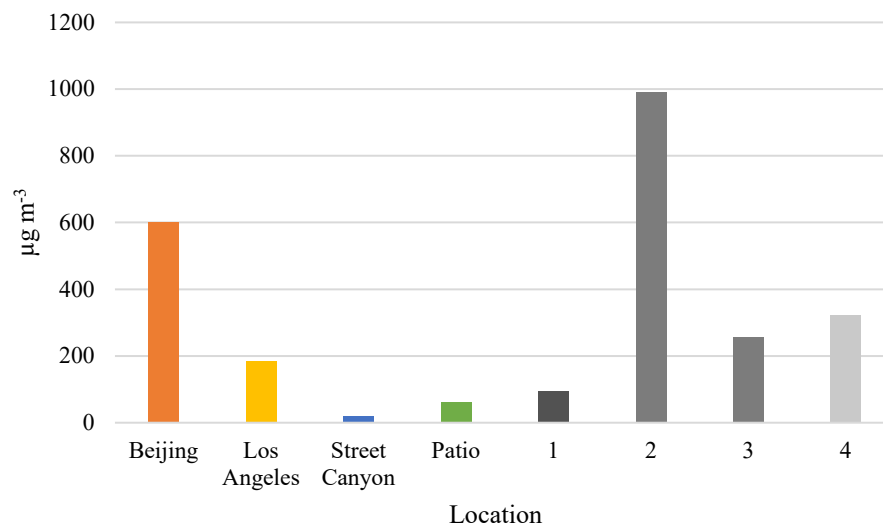
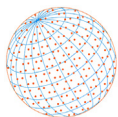


Fig. 4. Measured PM_{2.5} levels in Beijing (600 µg m⁻³), Los Angeles (185.9 µg m⁻³), a street canyon (19.4 µg m⁻³), and patios where second hand smoke exists (62 µg m⁻³), are compared with misting PM_{2.5} concentrations in Locations 1–4.

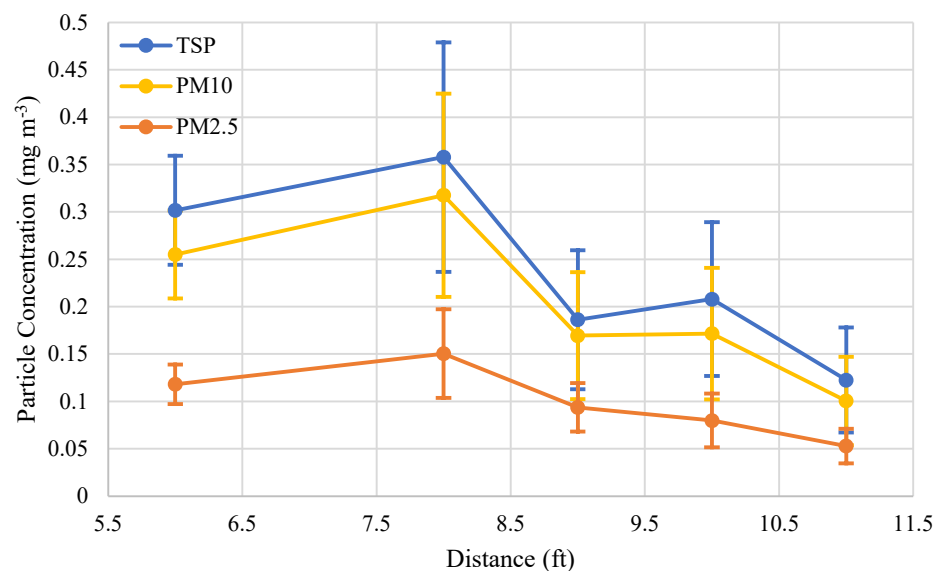


Fig. 5. Particle concentration vs. distance between sensor and misting system. Data were collected on three separate days where the dew point ranged from 16–39°F, 48–59°F, 49–60°F.

appear to be a downward trend with decreasing PM levels at greater distances from the misting system.

3.4 Ion Concentrations of Misting and Ambient Samples

A total of 19 PM samples and 3 water samples were collected and analyzed using ion chromatography. The chemical data were quite variable, which may be attributed to either the impact of background particles or due to low sample collection volume based on the low rate of the field sampler (3.7 L min⁻¹) and minimal sampling time. Converting from mg L⁻¹_(aqueous solution) to µg m⁻³_(airborne) involves dividing by the volume of air sampled. If the sampling time is small, the volume of air is small, causing the denominator to decrease and the final concentration of a contaminant to be higher than expected. The average concentrations of ion species detected in the samples are shown in Table 2. The data in Table 2 show that during misting periods, the ionic concentrations increase, except in the case of NH₄⁺ and NO₃⁻. Since no Cl⁻ peaks were detected in

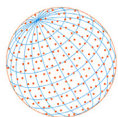


Table 2. Ion concentrations in source water as well as aerosol samples during misting operation and ambient (no misting system running) periods.

	Misting ($\mu\text{g m}^{-3}$)	Ambient ($\mu\text{g m}^{-3}$)	Ratio misting/ambient	Water (mg L^{-1})
F ⁻	-	-	-	0.56
Cl ⁻	71.1	< 8.2	> 9	356
NO ₃ ⁻	10.4	11.5	0.9	15.2
SO ₄ ²⁻	50.7	12.1	4.2	193
Na ⁺	36.3	3.90	9.3	85.2
K ⁺	1.29	0.80	1.6	3.81
NH ₄ ⁺	1.07	2.94	0.4	-
Mg ²⁺	11.7	0.23	51	41.1
Ca ²⁺	10.5	1.01	10	23.7

the chromatograms, the detection limit is reported. PM₁₀ data from a study conducted in Tempe and Phoenix were used to compare the ambient levels of Ca²⁺ and K⁺. The concentrations of Ca²⁺ and K⁺ from prior work in neighboring Tempe, AZ were 0.41 $\mu\text{g m}^{-3}$ and 0.459 $\mu\text{g m}^{-3}$, respectively (Upadhyay *et al.*, 2011). The ambient values of Ca²⁺ and K⁺ recorded during ambient periods were more than twice this previously reported PM level (Upadhyay *et al.*, 2011). Based on this limited analysis, no conclusive tracer can be determined as the sampling conditions were significantly different between studies.

3.5 Relation of Aerosol Composition to Local Drinking Water during Misting Periods

Table 2 compares also the air concentrations to water concentrations of the targeted ions. We see that the lowest differences between misting and ambient conditions are observed for NH₄⁺, NO₃⁻ and K⁺ consistent with ions that have very low concentrations in the local water. The highest enrichments between ambient and misting ratios are observed all for elements with high concentrations in the local tap water, indicating a clear impact of this source. Chloride and Magnesium stand out as in ambient air they are at or below detection limit but become major aerosol components during misting conditions.

Fig. 6 shows the concentration of Cl⁻ in samples plotted against the concentrations of Na⁺. The box in the figure represents the detection limit for each ion, calculated from the signal and standard deviation of the blank sample of Na⁺. For Cl⁻, the detection limit was estimated as half of the least concentration standard since no Cl⁻ peaks were seen in the chromatograms during ambient periods. Data were plotted against Na⁺ because the concentrations measured for Na⁺ were also relatively consistent between samples. Mg²⁺ was detected in some ambient samples not during misting, but the concentrations were very low. Initial review shows a similar trend in observed Mg²⁺ and Cl⁻ data. Linear regression was performed on the data in Fig. 6. The ratio of Cl⁻ to Na⁺ is one possible indicator that the PM in the misting samples is derived from supply water for the misting system; however, Cl⁻ is subject to acid replacement in aerosol particles and may not serve as a conserved tracer for misting system particle transport (Dasgupta *et al.*, 2006). F⁻ was included in the IC analysis since it is added to drinking water. F⁻ in the ambient and misting samples was not detected, but a small amount (0.56 mg L^{-1}) was detected in the non-diluted water samples. This measurement is also consistent with F⁻ concentrations as reported by the Scottsdale 2019 Water Quality Report (0.5 mg L^{-1}) (Scottsdale Water, 2019). Given this low concentration of F⁻, it is understandable that the very small amount of F⁻ in the source water would result in airborne concentrations below detection for F⁻.

3.6 Estimation of Amount of Particle Mass Flux

To assess the impact of misters on local air quality, a series of estimations was performed in an attempt to quantify the possible impact of misting systems on ambient PM levels. The first estimation used readily available data to estimate mass emission rates from the residential Orbit 12' Portable Mist Cooling Kit used in the controlled experiments. This system uses a water rate of ~0.03 liters per minute (LPM; Orbit, 2020). For comparison, estimations were also performed

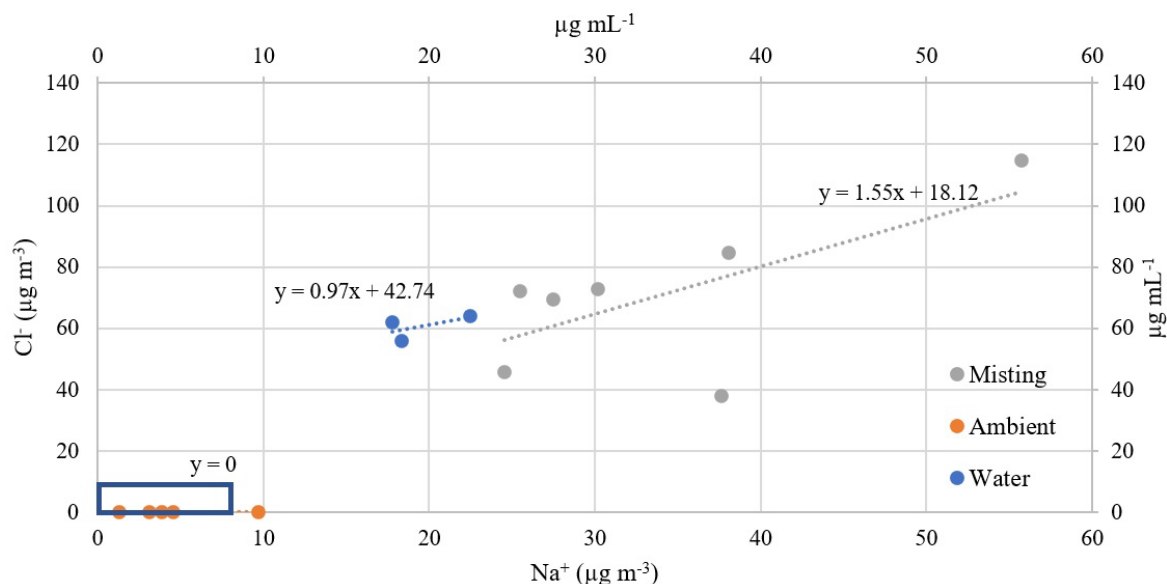
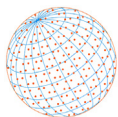


Fig. 6. Cl^- vs. Na^+ , plotted in $\mu\text{g m}^{-3}$. Cl^- detected in ambient samples was below the detection limit. Water samples are expressed in $\mu\text{g mL}^{-1}$ and the diluted sample (1:4) is plotted for ease of visualization. The box represents the detection limits of each ion.

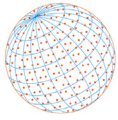
Table 3. Estimated mass flux of misting systems.

Type	Flow rate (LPM)	Mass flux (g hr^{-1})
Residential	0.03	0.9
Industrial (low flow)	1.9	60
Industrial (high flow)	7.6	230

for industrial misting systems, commonly connected to large industrial fans and present in livestock feeding lots. These misting systems are equipped with high pressure pumps and have variable flow rates ranging from $\sim 1.9\text{--}7.6$ LPM (Advanced Misting Systems, 2020). Using data from the Scottsdale 2020 Water Quality Report, the total dissolved solids (TDS) measured in the water ranged from $266\text{--}860$ mg L^{-1} (Scottsdale Water, 2020). A representative value of 500 mg L^{-1} of TDS was assumed to estimate the mass flux of each misting system assuming all water from the droplets evaporates based on the water flow rate as reported in Table 3. As shown in Table 3, emission rates from misting systems may range from ~ 1 gram per hour to hundreds of grams per hour depending on the size of the system.

3.7 Estimation of Particle Size

Another important consideration is the size of particles formed from evaporated mister droplets. Data was not readily available for the droplet size of water droplets generated by misting systems; therefore, a range of possible droplet sizes from 20 μm in diameter (based on typical sizes of cloud and fog droplets) (Zak, 1994; Fahey *et al.*, 2005; Herckes *et al.*, 2007) to 100 μm in diameter (when mist droplets develop significant settling velocity and are rapidly removed from the atmosphere) (Herckes *et al.*, 2002) is considered. Considering the TDS value of 500 mg L^{-1} according to the Scottsdale 2019 Water Quality Report, the volume of the original water droplet given the above size range, and assuming complete evaporation, the resulting aerosol particle would have a mass of between $2.1 \cdot 10^{-12}$ g and $2.5 \cdot 10^{-10}$ g. Assuming the resulting aerosol particle has a density of 1.5 g cm^{-3} (Pitz *et al.*, 2003; Hu *et al.*, 2012), the resulting particle generated by the misting system could have resulting diameters between approximately 1.4 μm to 6 μm . The results of this estimation are similar to the size of the observed increase in PM presented in Fig. 2. The data show that particles within the size class $\text{PM}_{2.5-10}$ were responsible for the overall increase in PM concentrations. However, observations also indicate that under different conditions, $\text{PM}_{2.5}$ was also responsible for the overall increase in PM concentrations.



4 CONCLUSIONS

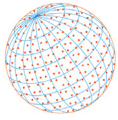
In this study, the impact of misting systems on PM concentrations was investigated during a controlled experiment in the backyard of a house and in four different public places. The effect of distance on PM concentration was also examined in the controlled experiment. PM and water samples from the controlled experiment were collected and were analyzed using ion chromatography. Data collected during this experiment show that misting systems cause elevated PM concentrations in a controlled experiment and in public places that have the potential to be of concern for human health. In the controlled experiment, the PM concentrations increase from an ambient level by a factor ranging from 4–14, with an average of 8. PM₁₀ in public places ranged from $102 \pm 10 \mu\text{g m}^{-3}$ to $1470 \pm 150 \mu\text{g m}^{-3}$, and PM_{2.5} ranged from $95 \pm 10 \mu\text{g m}^{-3}$ to $991 \pm 10 \mu\text{g m}^{-3}$. When distance between source and detector is changed, PM concentrations remain relatively constant then decline as the distance from a wall of misters increases. Ion chromatography analysis of PM and water samples showed that Cl⁻ and Mg²⁺ concentrations may be used as tracers of aerosolized water from misting systems since both ions showed a marked increase in their concentrations during misting periods of the controlled experiment. Calculations show that misters may be significant sources of PM in the respirable particle size range. Based on the data collected and calculations performed, we suggest that misting systems may be sources resulting in localized elevated PM levels and warrant further study.

ACKNOWLEDGMENTS

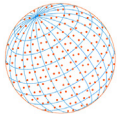
We are grateful to Jason Miech for assistance with ion chromatography analysis.

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