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Temperature Inversion and Ultrafine Particulate/Near Ultrafine Particulate Matter Concentrations in the Salt Lake Valley

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Abstract. Ultrafine particulate (UFP) matter exposures are associated with negative health outcomes. UFPs (<100nm) and near UFP (NUFP) matter (4.5nm - 250nm) are trapped by the bowl-like geography of the Salt Lake Valley causing winter inversions (i.e., trapped particulate matter (PM)). Enmont PUFP C100 and Grimm 1.109 particle counters were used to define NUFP concentrations during inversion (n=5) and non-inversion (n=5) days at 7 sites. NUFP concentrations served as a proxy for the UFP fraction. NUFP concentrations were log-transformed and multivariable mixed effects linear regression models determined if NUFP concentration differed between inversion and non-inversion or by length of inversion. Difference in fraction NUFP was also analyzed. The mean NUFP concentration was 1.49-fold higher during inversions (95% CI 1.11–2.02), whereas the fraction declined by 0.22 (95% CI -0.31– -0.13). Increased NUFP concentrations during inversions may lead to increased adverse health outcomes. These findings have serious implications for inversion-prone regions.

Keywords. Emerging issues, particulate matter, ultrafine, weather inversions, air pollution

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1. Introduction

Exposure to particulate matter (PM) poses significant acute and chronic health risks, particularly for those already experiencing adverse respiratory symptoms [1]. Chronic exposure to fine PM (2.5 µm and below, i.e., PM 2.5) from combustion sources is associated with higher mortality rates, particularly mortality associated with cardiovascular diseases, cancer, and diabetes [2-5]. Further, evidence to support an association between PM 2.5 exposures and the development of neurodegenerative disorders, such as dementia, is emerging in the scientific community [6-7]. Certain populations are more susceptible to experiencing these severe adverse health effects, including those with cardiopulmonary conditions, children under the age of 5, and the immunocompromised [8-11].

While the majority of scientific studies have focused on PM 2.5, an increasing body of evidence has linked these health impacts to ultrafine particulate (UFP) matter, or PM 100 nm or 0.1 µm and below [2]. Smaller particles (5 nm diameter) have been found to remain longer in the blood and urine than larger particles (30 nm diameter) [12]. Cardiovascular mortality in particular has been linked the exposure to UFP matter; both the California Teachers Study, a cohort of over 100,000 female participants, and the Intermountain Heart Collaborative Study linked ischemic heart disease events and mortality to UFP matter exposure [2, 6]. Additionally, several studies have indicated that the diameter and surface area of UFP matter alters its potential to cause biological effects at the cellular level, including inflammatory injury and oxidative stress [1, 13, 14].

Studies in high pollution areas, including Salt Lake City, Utah, have primarily focused on PM 2.5 as a possible trigger for adverse health effects such as emergency department visits for asthma [15]. Salt Lake City, like many high pollution areas, experience frequent weather inversions, a weather pattern that occurs when warm air traps a layer of dense, cold air beneath it, can increase exposure to particulate matter and may last anywhere from a few days to several weeks [16]. Other factors, including fog, reflection of light/heat by snow, and decreased wind speed increase the severity of the pollutant concentration [16-18]. Longer inversion episodes were linked with higher PM 2.5 concentrations, with inversions linked to exceedance of the National Ambient Air Quality Standards (NAAQS) for PM 2.5. [19, 20]. The American Lung Association (ALA) ranks metropolitan Utah areas, including Salt Lake City, as 7/186 for 24-hour particulate pollution [21].

The state's high pollution rankings and geographical features that compound the intensity and length of inversions make it an ideal site for investigating UFP matter concentrations. Although multiple studies have defined PM 2.5 concentrations during inversion episodes, few studies have been conducted to determine the concentrations of UFPs and near-ultrafine particulate (NUFP) matter (particles ranging 100-250 nm in diameter) during inversion and non-inversion events. We seek to quantify UFP/NUFP concentrations during inversion episodes compared to non-inversion episodes in the Salt Lake Valley. As children are especially vulnerable to air pollution events, we will conduct air monitoring at Salt Lake Valley elementary schools.

2. Methods

2.1. Sampling Locations

Schools within Salt Lake County's Granite and Salt Lake School Districts, as well as one private school, were chosen for this study to provide sampling sites representative of both healthy and vulnerable populations. Elementary schools represent exposure for young children, a vulnerable population, and the general population of school employees (e.g., teachers, teacher aides, crossing guards, and volunteers). Additionally, the vigorous public debate around whether or not to conduct or shorten recess periods during poor air quality days [22-24] makes defining UFP exposures near elementary schools particularly relevant.

The elevation of all sampling sites ranged from 1,293 to 1,382 m, bracketing the average elevation of Salt Lake Valley (1,320 m), increasing the likelihood that samples are representative of Salt Lake Valley UFP/NUFP concentrations as a whole [25, 26]. For reasons of convenience and limited resources, a sampling route was created that extended no farther than 5 miles at any point from our research lab at the University of Utah. In order to reduce possible confounding factors (i.e., traffic, weather), the route was also developed to ensure consistent sampling conditions (e.g., same time of day and similar traffic conditions) for all sampling days. Sampling locations were always on the same side of each school and on the same street to reduce variation in traffic patterns as much as possible.

2.2. Sampling

Samples were collected over two periods to record conditions of a weather inversion and a non-inversion period. The inversion sampling took place between Saturday, January 28, 2016 and Wednesday, February 1, 2017. Inversion conditions were defined by the forecasts given on the Utah Winter Fine Particulate Study (UWFPS) Cold Air Pool Forecasts [27]. Sampling began on the first full day of the inversion, as data on the inversion's severity was not available until the afternoon before, and then was repeated on the four subsequent days of the inversion. Two weekend days and three weekdays were included in the sampling schedule, which provided a variety of traffic conditions.

Control data were collected during a non-inversion period within approximately one month after initial sampling (Saturday, March 4, 2017 to Thursday, March 9, 2017). Sampling conditions between high exposure days and control days were kept as similar as possible, so there was less chance of experiencing confounding due to differences in human activities, atmospheric pressure, daylight, and weather patterns. Non-inversion sampling contained the same number of weekdays and weekend days as the inversion sampling. However, upon initial surveying of data for March 6, 2017, it was found that an instrument malfunction had occurred, with the one instrument reading high concentrations while the other and data from the Utah Air Quality monitor indicated low concentrations [31]. These data were therefore excluded and an extra day of sampling (March 9, 2017) was added. This was deemed necessary to provide an identical number of overall monitoring events for both inversion and non-inversion conditions.

All sampling events started between the hours of 8:00-9:00 am each day and ended between 12:00 pm-1:00 pm, with the exception of the one delayed inversion sampling event, which started shortly after 9:00 am. Each site was sampled for a total of 30 minutes (two instruments, each for 15 minutes). No validated sampling method was available, so a sampling procedure was created that would provide a sufficient representation of the air particle concentrations at each location by placing instruments in virtually the same location (atop the trunk of the car used) and aligning instrument sampling procedures as closely as possible.

Two direct-reading instruments were used, the Enmont Personal Ultrafine Particle Counter C100TM (Enmont, Cincinnati, Ohio) and the Grimm Optical Particle Counter Portable Aerosol Spectrometer 1.109 (GRIMM Aerosol Technik, Ainring, Germany). The Enmont uses water condensation particle counting technology to measure the count concentration of particulates in the air with diameters of 4.5 nm and above, with no cap on particle diameter size [28]. The GRIMM uses a laser diode to detect scattered light caused by the collected particles, measuring the concentrations in both mass and particle count measures of particles with diameters from 0.25 µm (250 nm) to 32 µm [29]. Data were downloaded and collected using Enmont Eview software and the Grimm 1.109 software, respectively. Although these two instruments use different methods to measure ambient PM concentration, they both provide a PM count concentration (particle count/volume) within their respective size ranges.

The instruments were run side-by-side in order to ensure that they were measuring the same air stream. Using both the Enmont and the Grimm enabled an estimation of the concentration of NUFPs only. As the Enmont measures particles with diameters ≥ 4.5 nm, it was necessary to subtract the Grimm-measured concentrations from the Enmont-measured concentrations for each sample in order to obtain the UFP/NUFP concentrations (diameters: 4.5 nm – 250 nm). The Grimm reported virtually no particles above 10 µm in diameter, making it unlikely that the Enmont collected particles with diameters ≥10 µm. The fraction of NUFPs compared to total particulates was also calculated by dividing the NUFP count concentration by the total PM concentration measured by the Enmont. Typically, UFPs are classified as particles <100 nm, so the range used in this study is a proxy for the true UFP fraction, as particles with diameters from 100 nm - 250 nm were included, giving a total size range of 4.5 - 250nm. All future references to NUFP in this study indicates this larger size range. However, as the purpose of this study is to quantify UFP concentrations, all results and conclusions about NUFP concentrations are meant to be extrapolated to UFP concentrations.

2.3. Statistical Analysis

All statistical analyses were run in the Stata IC 14.2 program (StataCorp, College Station, Texas). Before statistical analyses were performed, NUFP concentration values were tested for normality. The NUFP concentration was log-transformed for all analyses, as the concentration appeared to follow a log-normal distribution. Fraction NUFP values were left in the native scale but were scaled by 100 to allow for interpretation as percentage points.

NUFP count concentrations from inversion and non-inversion periods were compared with a multivariable mixed effects linear regression to account for correlation by sampling site. Fraction NUFP concentrations between inversion and non-inversion days were compared using the same model. A secondary mixed effects linear regression was also conducted to examine trends in NUFP concentration and fraction NUFP during inversions only. Each inversion day's NUFP concentration and fraction NUFP were compared to the first day of sampling as a reference to determine if there was a statistical difference. All p-values were considered significant at $\alpha = 0.05$.

Four meteorological variables, temperature, wind speed, humidity, and snow depth, were considered for inclusion in the linear regression as possible confounders. Meteorological data was collected from Meso West, a meteorologic database provided by the Department of

Atmospheric Sciences at the University of Utah [30]. Temperature, wind speed, percent humidity, and snow depth values were collected for times as close to actual sampling times as possible. Wind speed data was not available for 8 days in the control data set, so these days were excluded from the analysis. Before a final linear regression model was created, each meteorological characteristic was compared between inversion and non-inversion days using t-test statistics. Each variable was found to be statistically significant individually; however, the final linear regression model only included wind speed, as this was the only variable to significantly contribute to the model. The other meteorological variables were excluded from the final model as they were highly correlated with the presence or absence of inversion.

3. Results

Table 1 provides a summary of t-test results and summary statistics for all measured meteorological variables. Relative humidity and snow depth were significantly higher during inversions than non-inversions, as there was no snow coverage present on the ground during non- inversion days. However, wind speed and temperature tended to be higher during non-inversion days than inversion days.

Table 1: Summary of Meteorological Characteristics for Inversion and Non-Inversion Days

	Inversion (N = 35)		Non-Inversion (N = 35)		P-Value [a]	Correlation Coefficient [b]
	Mean (SD)	Range	Mean (SD)	Range		
Wind speed [c] (m/s)	2.13 (1.39)	(0.00 – 4.47)	6.85 (5.04)	(0 – 14.75)	<0.001	-0.55
Temperature (K)	268.78 (2.21)	(264.26 – 273.15)	284.26 (4.29)	(273.71 – 290.37)	<0.001	-0.92
Snow Depth (cm)	4.06 (1.26)	(2.54 – 5.08)	0 (0)	(0 – 0)	<0.001	0.92
Relative Humidity (%)	76.46 (6.90)	(62 – 88)	36.4 (10.13)	(21 – 64)	<0.001	0.92

SD = Standard Deviation
[a] P-value comparing inversion to non-inversion days
[b] correlation with presence of inversion
[c] 8 missing observations for wind speed

Results for the multivariable mixed effects linear regression comparing NUFP by inversion and length of inversion are summarized in Table 2. The geometric mean (GM) concentration of NUFP increased by 149% during the inversion episode relative to non-inversion days, controlling for wind speed (95% CI: 111%-202%, p<0.001). Figure 1 provides a comparison of NUFP concentrations between inversion and non-inversion episodes for each school. After controlling for wind speed, the GM concentration of NUFP did not significantly differ during Days 1-4 of the inversion. However, on the Day 5 of the inversion the GM concentration of NUFP showed a roughly two-fold increase relative to Days 1-4 (β=191%, 95% CI 132%-277%, p=0.001; ref=day 1). Figure 2 shows the distribution of NUFP concentrations by day of inversion, clearly showing the increase on Day 5 compared to Days 1-4 of the inversion.

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Table 2: Concentration NUFP

	exp(β)	95% Confidence Interval
Inversion [a]	1.49*	(1.11, 2.02)
Wind speed (m/s)	0.88*	(0.85, 0.91)
Length of Inversion		
Day 1	ref	
Day 2	0.83	(0.57, 1.21)
Day 3	1.13	(0.74, 1.72)
Day 4	0.75	(0.51, 1.10)
Day 5	1.91*	(1.32, 2.77)
Wind speed (m/s)	0.88*	(0.80, 0.98)

NUFP = Near Ultrafine Particulates
[a] Relative to non-inversion day
* Significant at p<0.05

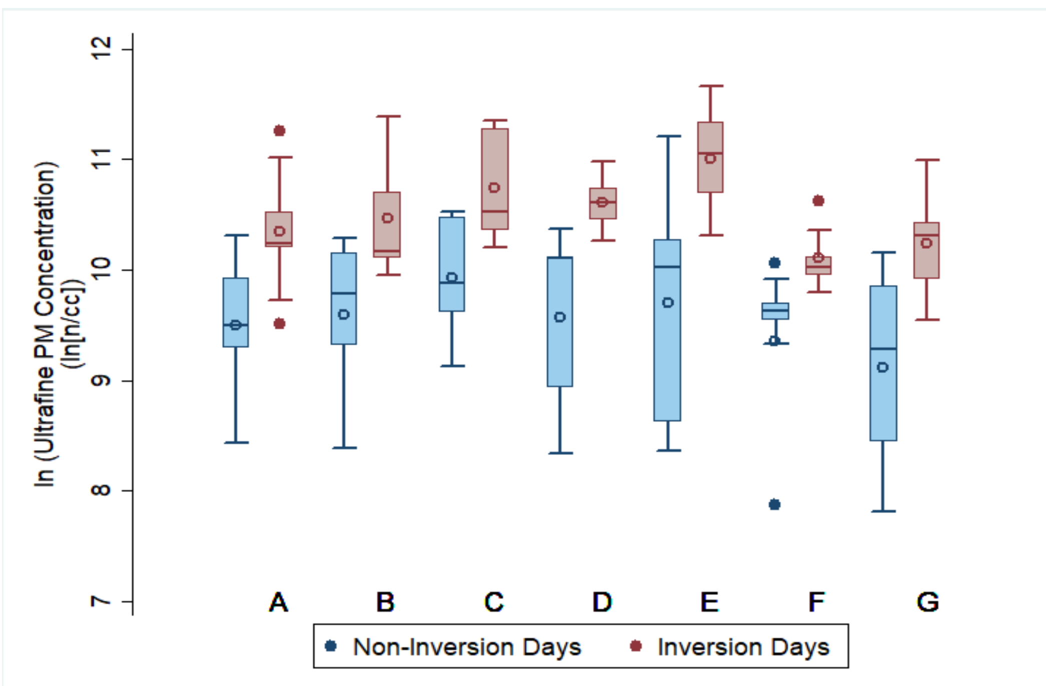

Figure 1. Comparison of NUFP GM Concentrations (ln[n/cc]) between Inversion and Non-Inversion Episodes. Center bar indicates median concentration; hollow circle designates mean concentration.

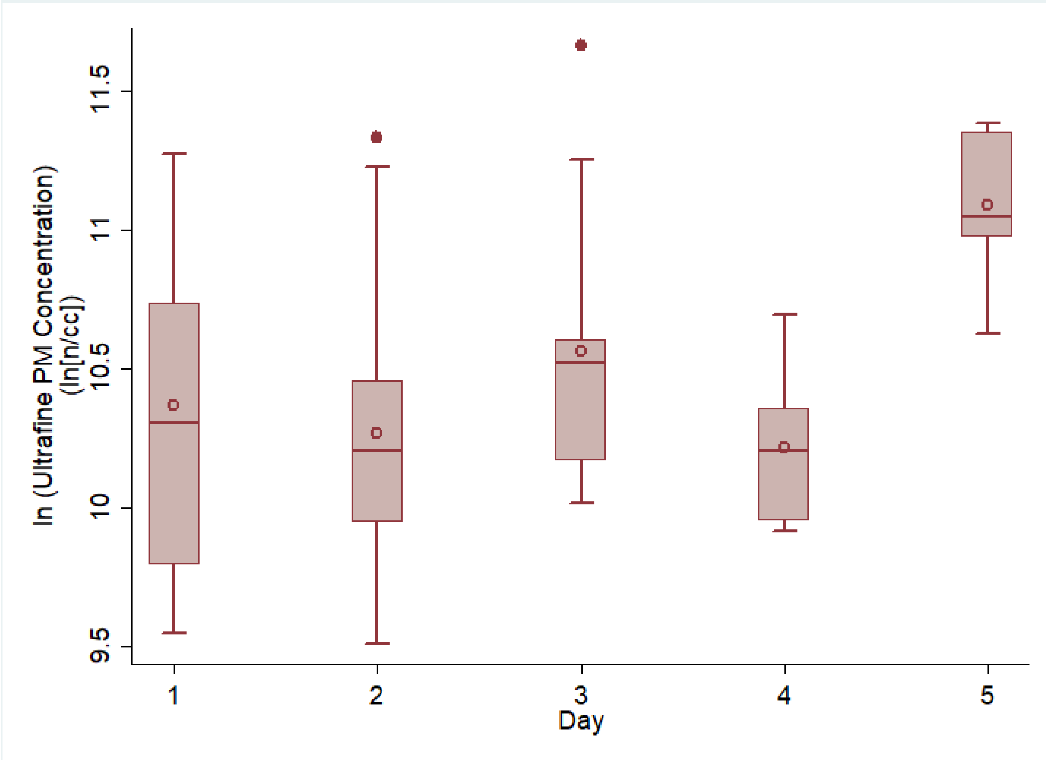

Figure 2. Impact of Length of Inversion on NUFP Concentration (ln[n/cc]). Center bar indicates median concentration; hollow circle designates mean concentration.

Analyses comparing fraction of total PM made up of NUFP by inversion and length of inversion were also carried out and are summarized in Table 3. The fraction of NUFP was statistically different during inversion episodes but only marginally lower in a practical application. Controlling for wind speed, the fraction of NUFP was 0.22 percentage points lower during inversions than non-inversions (95% CI -0.31 – -0.13, $p<0.001$). Although marginally lower during inversions, the average fraction UFP exceeded 99% of the total PM count concentration during both inversion (99.7%) and non-inversion (99.9%) episodes, indicating that while this difference is statistically significant, it may not have practical significance. Figure 3 provides a comparison of exposure values for fraction NUFP concentrations between inversion and non-inversion episodes at each school. In contrast to trends seen in NUFP concentration by length of inversion, a decline in fraction NUFP over the first 4 days of the inversion was observed after controlling for wind speed (trend= -0.14 percentage points/day, $p<0.001$). However, on the fifth day of the inversion, the fraction NUFP increased by 0.44 percentage points from the fourth day ($p<0.001$, not shown). This is likely due to the observed large increase in NUFP concentration on Day 5 of the inversion (Table 2, Figure 2). Figure 4 provides a comparison of fraction NUFP concentrations by day of inversion.

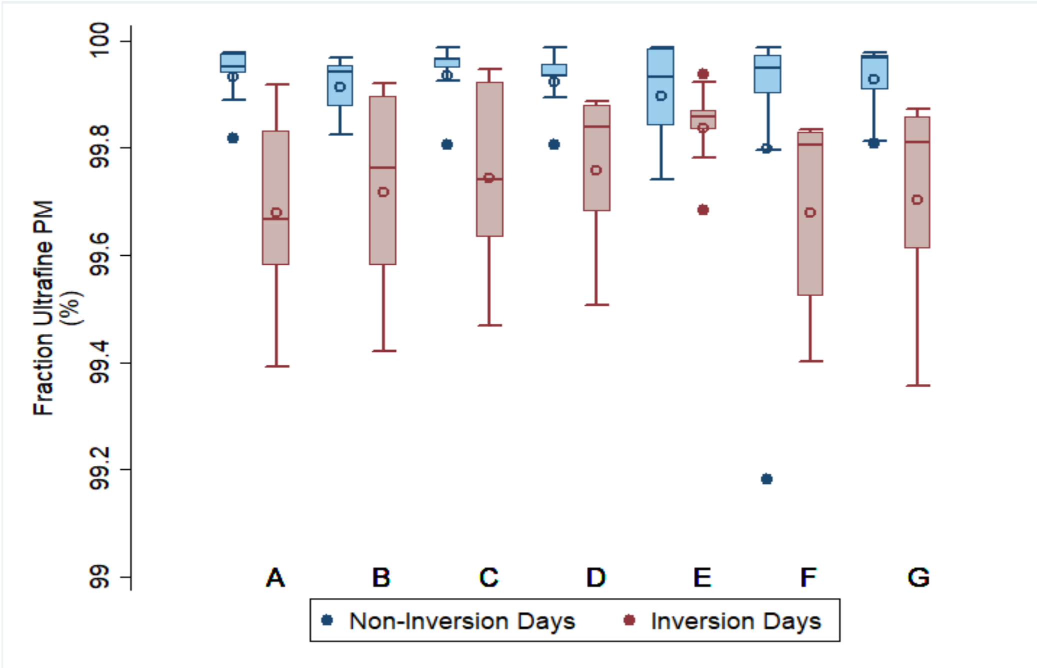

Figure 3. Comparison of Fraction NUFP Concentrations between Inversion and Non-Inversion Episodes. Center bar indicates median concentration; hollow circle designates mean concentration.

Table 3: Fraction Ultrafine PM

	β	95% Confidence Interval
Inversion [a]	-0.22*	(-0.31, -0.13)
Wind speed (m/s)	-0.01*	(-0.02, -0.00)
Length of Inversion		
Day 1	ref	
Day 2	-0.08*	(-0.14, -0.01)
Day 3	-0.23*	(-0.30, -0.16)
Day 4	-0.43*	(-0.49, -0.36)
Day 5	0.01	(-0.05, 0.07)
Wind speed (m/s)	-0.02*	(-0.04, -0.01)

[a] Relative to non-inversion day
* Significant at $p<0.05$

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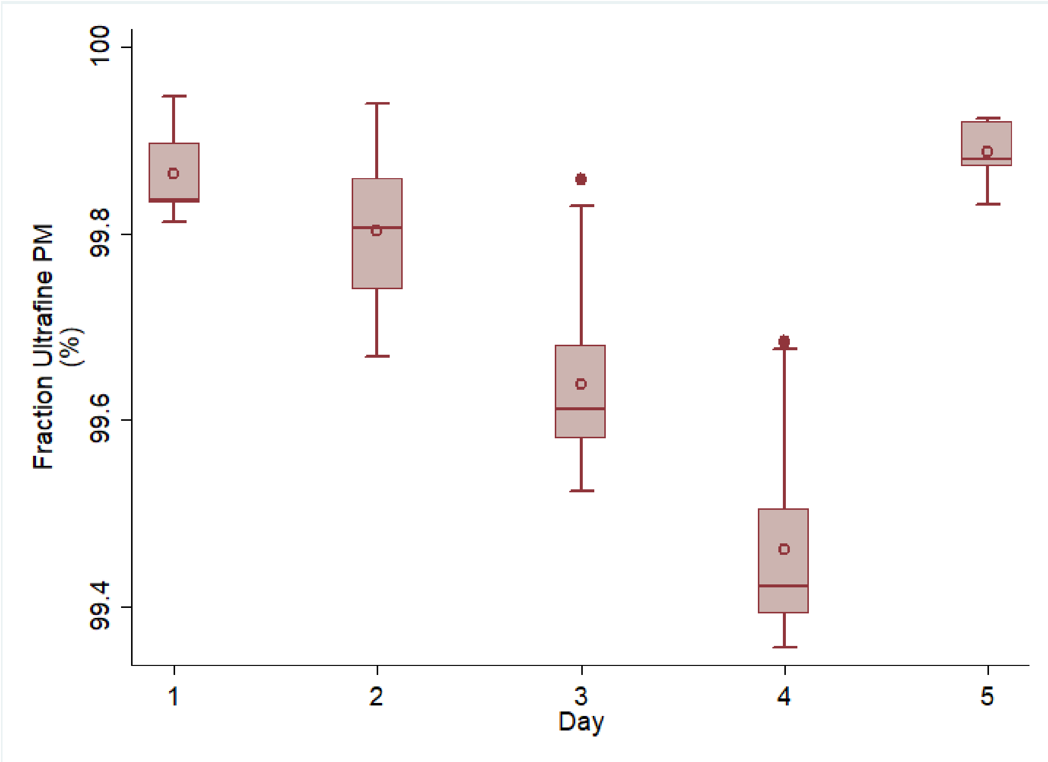

Figure 4. Impact of Length of Inversion on Fraction NUFP Concentrations. Center bar indicates median concentration; hollow circle designates mean concentration.

4. Discussion

Within the context of a growing body of evidence from various studies that UFPs pose a threat to human health, the results of this study are of concern. There was a statistically significant increase in GM NUFP concentrations (149%) between the measured inversion and non-inversion episode. The observed increase could easily translate into unhealthy levels of PM, particularly for those most vulnerable to air pollution. These findings suggest that continued research should be conducted to assess the severity of exposures throughout various areas in the Salt Lake Valley, as the area samples taken for this study are only indicative, rather than definitive, of personal exposures for vulnerable populations. In addition, a study on particle morphology as well as composition would be justified.

This study provides evidence for the hypothesis that UFP concentrations are higher during inversion episodes as was found for PM 2.5 in studies conducted in both Salt Lake and Cache valleys [18-20]. Larger, more detailed studies should be done to establish the associations between different meteorological conditions and duration of inversion and their effect on UFP concentrations. Including events from multiple inversions during the same winter and even multiple winter seasons would provide a wider range of conditions for analysis. An increase in sample size and more varied data points will add statistical validity and increased power for a greater evidenced-based understanding of UFPs during inversion episodes. Another approach to consider for future study designs is to include personal sampling methods in order to define exposures for specific vulnerable populations. Personal sampling for UFP exposures would provide more descriptive data concerning the exposures of these populations. Such studies could use the Enmont PUFP C200, which operates in a similar manner as the Enmont PUFP C100 and is specifically designed for personal sampling [28]. As more UFP studies are conducted with populations defined by vulnerability and by occupation, data can be used to guide the development of indoor/outdoor elementary school policies, as well as educating the general public about the health risks associated with weather inversions.

When analyzing the impact of the inversion's length on NUFP concentrations, the data revealed that concentrations were significantly higher on Day 5 of the inversion in comparison to Day 1; all other days were not statistically different in NUFP concentration. Additionally, the fraction NUFP was lower during Days 1-4 of the inversion, whereas Day 5 experienced an increase. Further data collection and analysis of the correlation between day of the inversion and NUFP concentration could be beneficial in assessing health risks, especially for longer inversion episodes. Based upon this study, inversions lasting 4 or fewer days may be less hazardous to the population's health than those reaching 5 days or longer. Findings from previous studies support this hypothesis [19]. In addition, Whiteman et al. found that PM 2.5 concentrations increased at a rate of approximately 10 $\mu g/m^3$/day during individual inversions in the Salt Lake Valley over a 40-year period [20]. While results from this study of NUFPs did not perfectly follow a steady increase in PM concentration by day, an increase in NUFP concentration on Day 5 may be in support of the 10 $\mu g/m^3$/day trend for PM 2.5. Further research is needed to confirm findings about the impact of an inversion's length on NUFP concentrations as the findings in this study are based on only one inversion episode. Inclusion of multiple inversion episodes from more than one winter season would be an ideal sampling method to follow. Knowing how long it takes for NUFP concentrations to increase and at what rate they increase by day during an inversion could also contribute to the development of policies and regulations concerning elementary school outdoor/indoor practices and vehicle use restrictions during inversion episodes.

The comparison of fraction NUFP during inversion days to non-inversion days produced results that were statistically significant but seemed to lack any practical significance, as the fraction exceeded 99% NUFP for both inversion and non-inversion days. This high percentage suggests that NUFP is an overwhelmingly significant contributor to inhalation exposures under both meteorological conditions. As research within the scientific community continues to uncover the adverse health effects of smaller-sized particles compared to larger-sized particles, this finding is relatively alarming [1, 12-14].

As noted previously, all measured meteorological variables differed significantly by inversion status. These observations are consistent with the known meteorological causes of inversions. During an inversion, normal atmospheric conditions are reversed, trapping cold air and pollutants in the valley beneath a layer of warmer air. (Utah Department of Environmental Quality 2018b) This results in stagnant, colder, more humid air within the valley. The differences in snow depth are due to the fact that many inversions happen during winter months when the snow accumulates and stays for days or weeks. Non-inversion samples were collected under meteorological conditions more indicative of spring weather than winter, so it was normal for there to be an absence of ground snow coverage.

4.1. Strengths

Despite lacking an established sampling method, necessary steps were taken to reduce the effect of possible confounders throughout the sampling process. While the method used for sampling was not derived from a standard method, it was in accordance with the manufacturer's instructions provided for each instrument. Potential confounders (i.e., temperature, humidity, wind speed, and snow depth) were considered and included appropriately in the statistical models, as these were found to be significant factors in previous inversion studies [18,20]. A sufficient number of convenience samples were collected to increase the level of confidence in sample parameter estimates. Consistency in sampling times and locations reduced discrepancies between sampling sites, which could have introduced confounding factors. Because all locations selected were within a reasonable range of the average Salt Lake Valley elevation (1,320 m), the comparison between inversion and non-inversion data is applicable to the entire Salt Lake Valley, adding greater generalizability in the context of Salt Lake Valley populations. Other possible confounders, such as time of day of sampling and traffic patterns, were controlled for by sampling on a consistent route each day and including the same number of weekdays and weekend days in the sampling plan.

Inclusion of wind speed, which was significant in the t-test statistics, in the mixed effects linear regression model increases the statistical validity of the results. The possibility of confounding from wind speed on the difference in NUFP concentrations was accounted for due to this analysis. Conclusions concerning the significant difference in NUFP concentrations and fraction NUFP can be made with greater confidence after controlling for wind speed in the mixed effects linear regression. Excluding temperature, humidity, and snow depth from the final linear regression model also strengthened the results as these variables did not strengthen the analysis due to their being highly correlated with presence of inversion.

As the study of UFPs is an emerging issue in the world of environmental and occupational health, new technologies are emerging that have yet to be used in a wide array of studies. Including both the Enmont Personal Ultrafine Particle Counter C100TM and the GRIMM 1.109 provides future studies with a reference for possible sampling methods and appropriate use of each instrument. As the Enmont is a newer instrument on the market, few studies have used it in their sampling methods.

4.2. Limitations

While the results of this study are valid and beneficial, some aspects of the study design limit the conclusions that can be drawn. Because samples were taken from only one inversion episode, generalizability is limited and the results not may apply to other inversion episodes in the Salt Lake Valley with different characteristics (e.g., duration, amount of snow, higher or lower temperatures and wind speeds). Some factors that could not be controlled at each sampling site included presence of idling school buses, passing of large diesel trucks near the sampling site, or lack of traffic at certain sites on some days.Varying weather conditions and fluctuating traffic patterns during inversions will affect NUFP concentrations as well. Conclusions drawn from this study can be considered relevant to the growing body of information concerning NUFP concentrations, but are not generalizable to all inversions. Additionally, these results are limited by Salt Lake Valley geography. Other valleys will have varying geography that would affect NUFP concentrations in a different way than those experienced within the Salt Lake Valley. The results of this study can suggest possibilities for other valleys' concentrations, but they cannot predict the exact patterns that may occur.

Another aspect in which this study was limited is that collected samples were of area concentrations rather than personal exposures. As such, results and conclusions may not be applicable to specific individuals throughout the Salt Lake Valley. Sampling locations may not be representative of individual exposures for those working at elementary schools or for vulnerable populations. Having individuals wear personal particulate monitors would have provided more comprehensive results for defining the exposure of both healthy and vulnerable populations, as was done in a study by Ryan et al. (2015) [32]. Following this sampling method for future studies in the Salt Lake Valley could provide further insight into the UFP exposures experienced by both healthy and vulnerable populations.

It should also be noted that the statistical analyses were run using concentrations that included particles with diameter sizes up to 150 nm larger than what is typically considered as part of the UFP fraction. Although this limits the conclusions that can be drawn for a strictly UFP fraction, the inclusion of particles with a diameter size down to 4.5 nm allows the results to be indicative of how a UFP concentration would act during inversion and non-inversion episodes.

5. Conclusion

Results from this study suggest that UFP concentrations during inversion episodes are significantly higher than non-inversion episodes in the Salt Lake Valley. The multivariable mixed effects linear regression, which includes wind speed as a possible confounder, indicates that NUFP concentrations were significantly higher during the most severe inversion episode of the 2016-2017 winter season compared to one non-inversion episode. These findings align with other studies that similarly found increased PM 2.5 concentrations during inversions. Additionally, findings from this study support the hypothesis that longer inversion episodes are associated with higher PM concentrations, therefore making it likely that they are associated with increased risk for adverse health effects for total and vulnerable populations.

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