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Concentration gradient patterns of traffic and non-traffic generated fine and coarse aerosol particles.

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Abstract

This research project was undertaken to establish baseline information for Health Impact Assessment (HIA) project of Interstate-75 road construction in Cincinnati, OH. The objective of this study was to evaluate the concentrations of elemental and organic carbon (EC and OC), as well as characterize particle number concentrations using devices that measure the fine fraction in the range of 0.02 – 1 µm and the coarse fraction up to 20 µm. The measurements were conducted at two sites located in a proximity of an interstate highway (at 124 and 277 m) as well as at a remote control site (at >2000 m from any interstate highway). Samples were collected for 24-hours over twelve days in each season (summer, fall, and winter). Wind data were obtained from the area weather station. Data were analyzed using mixed linear models. Significant increases in concentrations of EC, OC, and fine particles as well as in EC/OC ratios was observed with decreased distance to the highway and this difference was more pronounced in the fall. These results suggest that residents and workers in areas near high traffic highways, may be exposed to elevated levels of airborne fine particles. The results can be used as baseline for future HIA of road construction in the area.

INTRODUCTION

The HIA is a tool that provides decision makers at the city, county, State and the federal level with information on how a policy will potentially affect the health of the population. The 'recommendations' of HIA projects are evidence-based and geared towards maximizing positive health impacts by removing or minimizing the negative health impacts on the population (Taylor and Quigley, 2002). Health effects occupy the focal point in decision making policies outside of the health sector. Highway traffic in urban areas is a significant contributor to the total airborne particulate concentration. Several studies have suggested that exposure to traffic generated aerosols exacerbate asthma in patients living near highways (Holguin, 2008). Children are particularly susceptible to these aerosols, due to their developing respiratory system and could be adversely affected if they reside close to

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highways (Gauderman et al., 2007). Even short term exposure to traffic related particles has been shown to reduce lung function in atopic schoolchildren (Barraza-Villarreal et al., 2011).

$PM_{2.5}$ is defined as airborne particulate matter with an aerodynamic diameter less than or equal to 2.5 μm. They are most often produced via combustion (US EPA, 2008). Due to their small size, these particles penetrate deep into the respiratory tract, creating the potential for adverse health effects (US EPA, 2008). $PM_{2.5}$ mass concentrations do not vary greatly with differing distances from highways (Martuzevicius et al., 2004; Roorda-Knape et al., 1999) and are only slightly affected by traffic density (Martuzevicius et al., 2005). A more clear effect of traffic sources has been observed for fine (particles < 1 μm in diameter) and ultrafine (<0.1 μm) particles (Zhu et al., 2002; Reponen et al., 2003; Zhu et al., 2009).

Kim et al. (2004) have reported that the concentrations of black carbon (organic carbon and elemental carbon) were higher in areas within 300 m of highways compared to background. While organic carbon (OC) is produced by all combustion sources, elemental carbon (EC) is primarily generated by traffic sources, particularly diesel burning vehicles (Birch and Cary, 1996). As such, EC is frequently used as a surrogate for traffic generated aerosols (Holguin, 2008; Ryan et al., 2009). It is reported that EC concentrations are greater in areas near highways and increase with increased truck traffic (Kinney et al., 2000; Lena et al., 2002; Martuzevicius et al., 2004). The ratio of elemental carbon to organic carbon (EC/OC) provides an estimate of the overall percentage of the total carbon (EC + OC) that can be attributed to combustion of diesel. Where traffic exhaust is the primary source of diesel and combustion exhaust, this ratio is used to indicate the fraction of the total carbon attributable to diesel consuming vehicles (Maykut et al., 2003).

Interstate highways, major traffic arteries in the USA, undergo through various improvements, especially in major metropolitan areas known for traffic congestions. Widening highways by adding lanes allows for higher traffic volume, which may increase the traffic aerosol emission. An improvement of Interstate 75 (I–75), a major north-south transportation corridor, is currently in the planning phase in the Greater Cincinnati area. This will include adding one lane in both directions, which may result in potential health implications for residents in the construction area – mostly low income population. In this light, an HIA of the construction site was initiated to obtain baseline air quality information, followed by assessment of air quality during the construction and after its completion.

The distance traveled by highway-generated airborne particles of different sizes is unknown for highways in the Greater Cincinnati area. Furthermore, the effect of future road construction on the local air quality is not clear. This case study investigated particle number and mass concentrations of fine and coarse particles as well as EC, OC, and $PM_{2.5}$ at different distances from an interstate highway in order to create a baseline data set for future HIA.

METHODS

Site Selection

Three sampling sites were selected based on direction and distance from a high traffic highway in Cincinnati, Ohio and are further referred to as Site 1, Site 2, and Site 3 (Figure 1). Sites 1 and 2 located respectively at 124 m and 277 m from I–75 (Site 2 was initially chosen at 283 m but moved 6 m closer after the first sampling period). Site 3 served as a background station located at >2,000 m from any interstate highway in the metropolitan area. The sites were selected northeast and downwind of the closest highway [based on the pre-dominant wind direction in Cincinnati (Martuzevicius et al., 2004)] and far away from major coal fired power plants. Stations 1 and 2 were placed on the roofs of buildings (at the heights of 7.6 and 19.5 meters, respectively) and the background station 3 was placed on the ground. The traffic volume on the highway nearby sites 1 and 2 was 142,500 cars and 19,000 trucks per day. The respective numbers on the highway nearest to Site 3 were 82,400 and 9,100.

Aerosol Sample Collection

Ambient air sampling was conducted during three seasons (summer and fall of 2010 and winter of 2011). A total of four Harvard $PM_{2.5}$ Impactors (MS&T area sampler; Air Diagnostics Inc., Harrison, Maine) were utilized on the three sites. Twelve 24-hour samples were collected at a flow rate of 20 l/min during each season. The sampling was carried out on days with limited or no rainfall. At each of the three sites, particulate matter was collected onto 37-mm Quartz filters that were analyzed for EC and OC concentrations using evolved gas analysis (EGA) by a thermal optical analyzer, as performed by a commercial laboratory (Chester LabNet, Tigard, Oregon). An additional (the fourth) $PM_{2.5}$ sampler was deployed at Site 1 to collect samples onto 37-mm Teflon filters that were analyzed gravimetrically.

Each station was equipped with two real-time particle measurement devices: a P-Trak condensation nuclei particle counter (TSI Inc., St. Paul, Minnesota) and an ARTI optical particle counter (Hand Held Particle Counter-6; Hach Company, Loveland, Colorado). The P-Trak measures the total number concentration of airborne particles in the size range of 0.02–1 μm (fine particles), whereas the ARTI measures the particle number concentration size-selectively in the size range of 0.7–20 μm (mostly coarse particles). The real-time data generated by both instruments were recorded as three-minute averages. The instruments were operated from 8:00 am to 6:00 pm on each day when the filter samples were collected; however, in some cases only a portion of this 10-hour window was found useful (the limitation was due to technical problems such as rapid evaporation of isopropanol in a condensation nuclei counter, especially in summer, and malfunctioning of pumps during long-term sampling). As a result, the real-time data obtained from 9:30 am-12:30 pm were utilized for analysis because these measurements were consistent at all three sites and ANOVA demonstrated that the average concentrations calculated from the data collected from 9:30 am to 12:30 pm did not differ from the overall average values determined for the entire 10-hour period ($p > 0.05$). Average concentrations were used instead of hourly data because cumulative exposure values are more relevant for the future HIA.

Data Analysis

The statistical modeling was performed for EC, OC, EC/OC ratio, $PM_{2.5}$ mass and number concentrations of fine and coarse particles. Data were found to be normally distributed when log transformed. Geometric means and 95% confidence intervals were calculated for all particle concentrations. The arithmetic mean was also calculated for $PM_{2.5}$, so that data could be compared with the National Ambient Air Quality Standard (NAAQS) (US EPA, 2011).

Wind speed and direction were obtained from data gathered at the nearest National Weather Service sampling location, 8 miles from Sites 1 and 2 and 24 miles from Site 3. Daily averages of the available hourly values were determined for each 24-hour filter collection period – from 8 am to 8 am the following day. Additionally, averages of the hourly values between 9 am and 1 pm were determined to relate to real-time samples. A wind index was calculated for each site as follows:

$$Wind\ Index = \frac{1 - \cos(\theta - x)}{2} \quad (1)$$

where Θ = the angle (Θ) of the site to the nearest highway and x = wind direction (Figure 2) (Ryan et al., 2008).

The wind index is a rescaling of the difference in the angle to nearest major traffic source and predominant wind direction to a scale of zero to one. The wind index is a continuous variable with sites directly upwind of the nearest traffic source having a wind index equal to zero, sites directly downwind of the nearest traffic source had a wind index equal to one, and sites perpendicular to the wind direction had an index of 0.5.

For all analyses, sample days missing data from any three sites were excluded. Each data set was then analyzed for spatial and seasonal variation using a linear mixed model (SAS 9.2 software; SAS Institute Inc., Cary, North Carolina); adjusting for wind speed and calculated wind index. The mixed model was also used to compare wind speeds and wind indexes between the sampling seasons. A p-value less than 0.05 was considered statistically significant.

RESULTS

The geometric means and 95% confidence intervals for $PM_{2.5}$, EC, OC, EC/OC and the number concentrations of fine and coarse particles are presented in Table 1. $PM_{2.5}$ concentrations varied from 5.4 to 34.4 μg/m^3 having a geometric mean of 15.4 μg/m^3 and an overall arithmetic mean of 17.0 μg/m^3. Daily average concentrations of EC varied from 0.06 to 2.91 μg/m^3 (GM=0.53 μg/m^3) whereas OC concentrations were higher, varying from 0.73 to 10.35 μg/m^3 (GM=3.53 μg/m^3). The EC/OC ratios varied from 0.04 to 0.48 (GM=0.15). The number concentrations of fine particles, as measured with the P-Trak, ranged from 2,991 to 42,749/cm^3 (GM=12,628/cm^3). Considerably lower particle number concentrations were measured with the ARTI for large particles: 268 – 8,872/cm^3 (GM=1,267/cm^3).

Table 2 presents wind speeds and indexes. On average, the sampling sites were neither up nor downwind of the source based upon the wind index and were not significantly different between seasons. However, a significant difference in the wind index between sites was observed in the summer (p=0.006, Table 2). Therefore, statistical analyses presented in Table 3 and 4 on the concentration data were adjusted for wind data. Wind speed was strongest in the winter and weakest in the summer (p<0.001). Given that the original wind data were obtained from a single weather station, the same wind speed was used for each sampling site.

The geometric means of the EC and OC concentrations and EC/OC ratios at each site are presented in Figure 3 and the results of analyses in Tables 3 and 4. EC concentrations decreased with increasing distance from the nearest interstate highway and the differences were significant between sites (p<0.001; Table 3). As expected, Site 1 had the highest EC concentration and Site 3 had the lowest EC concentration for all seasons. The EC concentrations were lowest in winter and highest in fall (p=0.004; Table 4). Similar to EC, OC concentrations decreased consistently in all sampling seasons with increasing distance from the nearest interstate highway (Table 3). In all seasons, Site 1 exhibited the highest OC concentration and Site 3 had the lowest OC concentration (p<0.001). No significant differences were found in OC concentrations between the different seasons (Table 4). EC/OC ratio was highest at Site 1 and lowest at Site 3 (Table 3). The highest EC/OC values were identified in the fall. The seasonal differences were significant between fall and summer (p=0.031; Table 4) and between fall and winter (p<0.001).

Sampling for $PM_{2.5}$ was only conducted at Site 1. $PM_{2.5}$ concentration was significantly lower in the fall than in the winter (p=0.027; Table 4).

The geometric means for number concentrations of fine and coarse particles measured at each of the three sites during the three sampling seasons are shown in Figure 4. Some lack of consistency in performance of the real-time particle monitoring instruments resulted in varied sample numbers between seasons. The concentrations of fine particles were significantly different between sites. The particle number concentration at Site 1 was greater than at Site 2 (p=0.007) and Site 3 (p<0.001), and the concentration at Site 2 was greater than at Site 3 (p=0.002) (Table 3). Fine particle concentration was lower in the summer than in the fall (p=0.025; Table 4). The average concentrations of coarse particles were highest at Site 3 in summer and winter, but this difference was not statistically significant (Table 3). Seasonal variation of large particles was not significant either (Table 4).

DISCUSSION

We found that the concentrations of EC, OC, and the EC/OC ratio were significantly greater at locations nearest the highway, suggesting that traffic is a major contributor to these ambient aerosols. Our results support data reported by Kim et al. (2004), which revealed that the concentration of traffic-related air pollution decreases downwind from the highway.

A similar decreasing trend was observed for the number concentrations of fine particles, suggesting a concentration gradient also exists for fine particles with respect to distance. It should be noted that the sampling stations were located at different heights. However, Hitchins et al. (1999) have shown that the sampling height did not affect the concentration of fine particles at distances of 80 and 210 meters from the highway. While the measured particles are not necessarily all traffic related, our data suggests that the aerosol concentration in the size range from 0.02–1 μm is greater in areas near a highway with intense traffic. Investigations in other cities have indicated that number concentrations of fine particles decrease to the background level at a distance of about 300 m from highways (Zhu et al., 2002; Zhu et al., 2009). Reponen et al. (2003) reported that the spatial variation between 400 m and 1600 m from a highway was not significant. The current study shows significant differences between sites 124 m and 277 m from the nearest source and significant differences between both of these sites versus the "background" site located more than 2000 m away from highways. While the spatial variation reported in this study appears to be somewhat different from the one reported by Reponen et al. (2003), the number concentrations of fine particles, which ranged approximately from 1.5×10^4 to 2.0×10^4 $1/cm^3$, were similar.

The number concentration of coarse particles was higher at Site 3 compared to Sites 1 and 2, though this difference was not statistically significant. This may be attributable to the increase in landscaping activities taking place at Site 3. During both seasons, lawn care companies were in the area surrounding Site 3 up to five days a week. The location of this sampling site on the ground may have increased the contribution of local sources, which is a limitation of the present study. There is limited information available on the horizontal and vertical variation of coarse particles (Cheung et al., 2010 and 2011) and therefore, the impact of the differing sampling height is difficult to estimate. However, it is notable that the effect of landscaping activities was not seen in OC concentrations. It was apparent only for the number concentrations of coarse particles measured with an optical particle counter. Our results are consistent with those presented by Pabkin et al (2010), who concluded that traffic is the major source for both fine and coarse particles near highways, whereas natural sources, such as windblown dust, dominate in more rural areas. Future HIA studies should include chemical speciation of the coarse particle size fraction. This would allow more clear differentiation of the effects of traffic and road construction.

A clear seasonal variation was observed for most of the studied particle types. Concentrations of EC and fine particles as well as EC/OC-ratio were highest in the fall. In contrast, concentrations of $PM_{2.5}$ were lowest in the fall. Martuzevicius et al. (2004) have reported similar seasonal variation suggesting that it is the result of coal powered power plants being the primary $PM_{2.5}$ contributor in the Greater Cincinnati area and increased energy usage during summer and winter. The fact that samples were only collected on days with limited or no rainfall and low wind speeds largely limits the influence of weather related phenomena. The results indicate that the effect of traffic on the aerosol concentrations is greater in the fall than in the summer and winter, when other aerosol sources appear to be more dominant.

The highest measured concentration was close to the 24-hour fine particle threshold listed in the National Ambient Air Quality Standard (NAAQS) of 35 $\mu g/m^3$ (EPA, 2011).

Furthermore, the overall average of the 24-hour PM2.5 samples (17.0 μg/m^3, n=36) exceeded the annual $PM_{2.5}$ NAAQS of 15.0 μg/m^3.

Our results suggest that residents and workers in areas near high traffic highways may be at increased risk of experiencing negative effects from traffic related aerosols. High background level of $PM_{2.5}$ adds to overall particle exposure. Future road construction will likely lead to increase in concentrations of fine and coarse airborne particles as a result of congested traffic (Keuken et al., 2010), changing traffic patterns, and the construction activity itself. It is also possible that the concentrations observed after construction may decrease due to more efficient traffic patterns. On the other hand, the above positive outcome may be diminished if the increase in road space will increase the traffic density over time. To determine the true trend of air pollution associated with the highway improvement, it seems useful to conduct similar sets of measurements during and after construction.

The road construction/demolition can also indirectly affect the health of citizens Wernham (2011). New traffic patterns may increase the risk of traffic-related injuries. Furthermore, the roadway might unintentionally cut off an important walking route to and from a transit stop or local school, making it harder for adults and children to get enough exercise.

These are significant health concerns. It is estimated that health problems associated with our current transportation system - such as injuries, asthma, cardiovascular disease and premature mortality - may result in over $300 billion in additional costs every year. This amount includes accidents and medical expenses, as well as lost wages and lost productivity (Wenham, 2011). One way to reduce the negative impacts of transportation is the HIA, which is a powerful tool being used worldwide to identify unintended health risks and unnecessary costs.

CONCLUSIONS

In summary, the concentrations of EC, OC, fine particles and the EC/OC ratio were significantly greater at locations nearest the highway, suggesting that traffic is a major contributor to these ambient aerosols. The concentrations of EC and number of fine particles as well as EC/OC-ratio were highest in the fall, whereas the concentration of $PM_{2.5}$ was lowest in the fall; these findings suggest that the effect of traffic on the aerosol concentrations in this area is more pronounced in the fall.

This study was undertaken to provide decision makers with a tool to assess the exposure and consequently the health impact of the future infrastructure improvement to I–75 in the Greater Cincinnati Area. The main outcome of the study is a baseline aerosol database to be used in a follow-up HIA evaluation.

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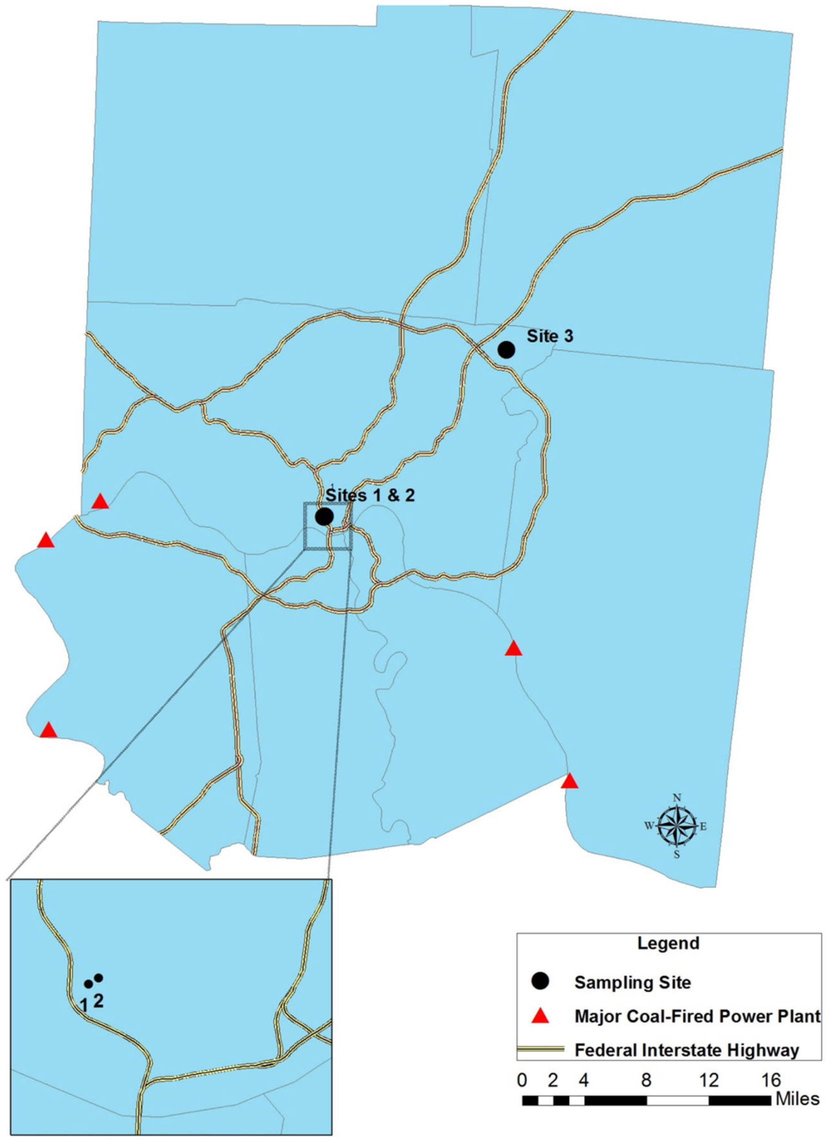

Figure 1.
Location of sampling sites in relation to highways and major coal fired power plants.

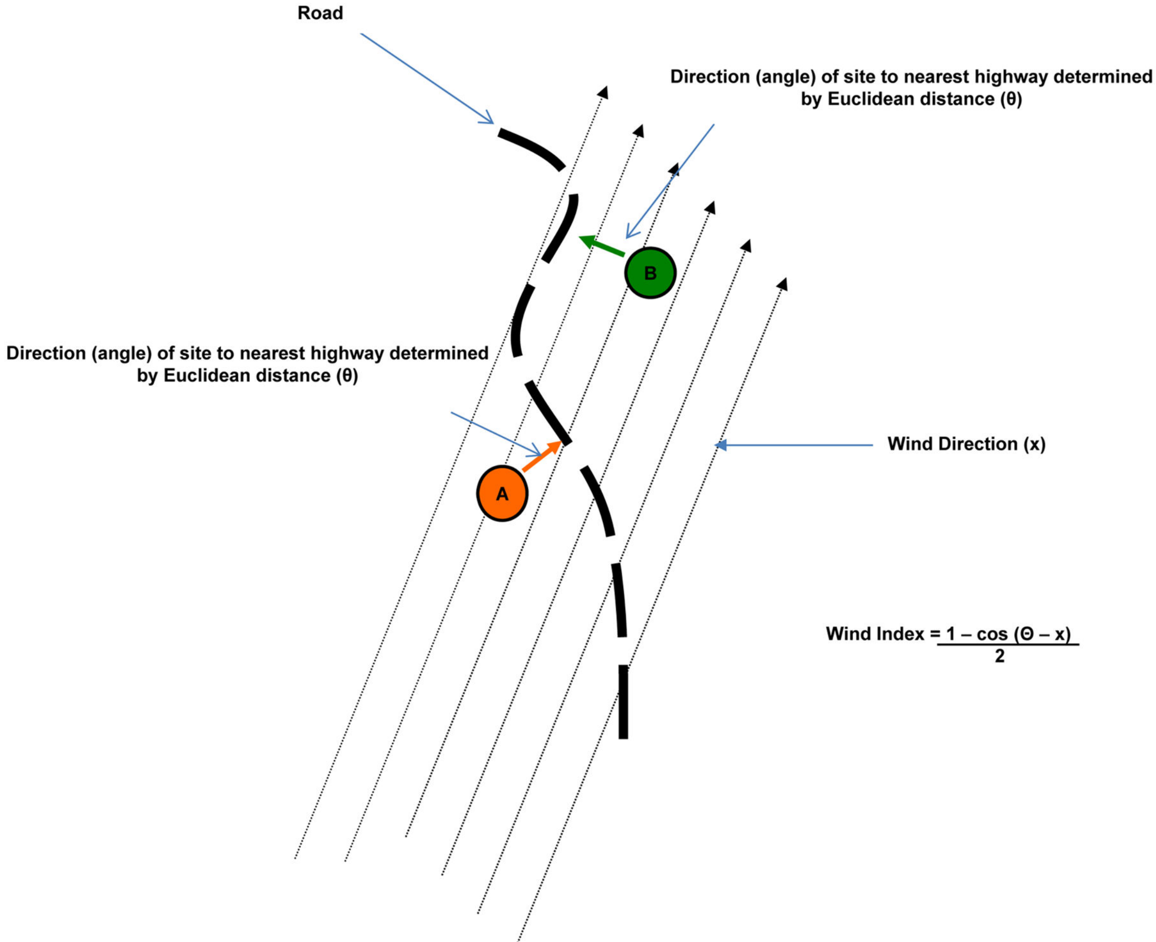

Figure 2.
Calculation of wind index.

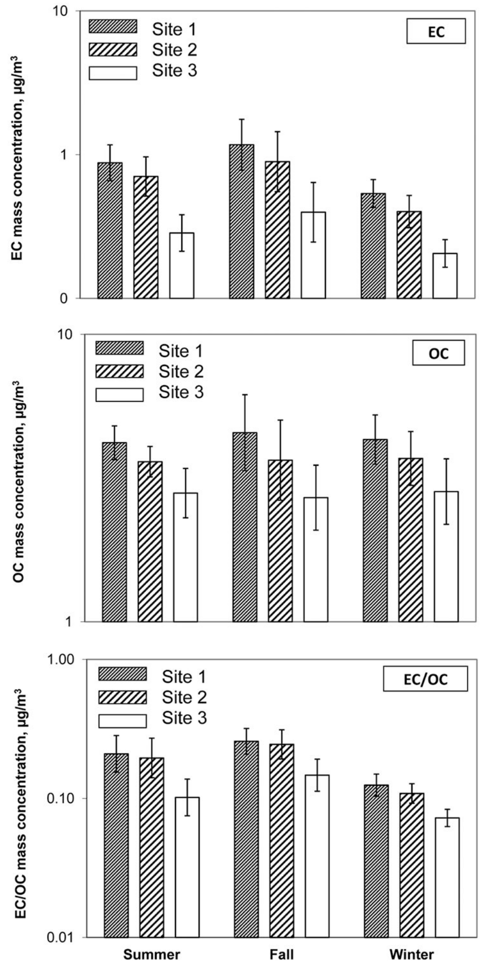

Figure 3.

Geometric means and 95% confidence intervals for the concentrations of elemental carbon (EC) and organic carbon (OC) and EC/OC ratio (n=12).

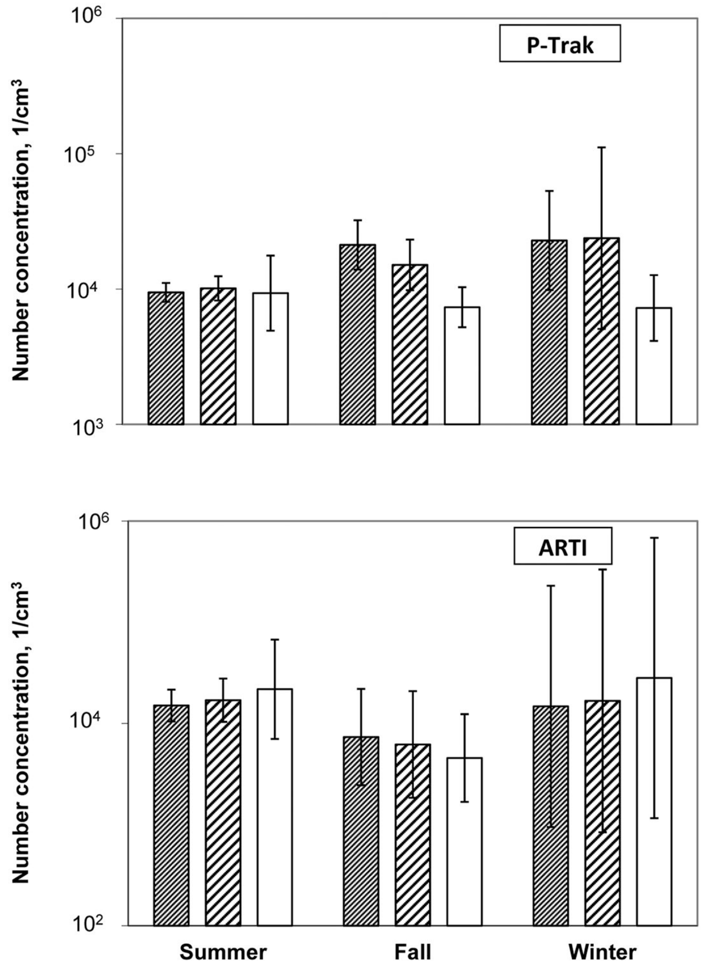

Figure 4.

Geometric means and 95% confidence intervals for fine particle concentration measured with a P-Trak (summer: n=4, fall: n=8, winter; n=3) and for coarse particle concentration measured with an ARTI (summer: n=5, fall: n=4, winter: n=3).

Table 1.

Geometric means and 95% confidence intervals.

Measured parameter	Geometric Mean	95% Confidence Interval
$PM_{2.5}$ (μg/m^3)	15.4	13.3 – 17.8
EC (μg/m^3)	0.53	0.46 – 0.61
OC (μg/m^3)	3.53	3.28 – 3.81
EC / OC	0.15	0.14 – 0.17
Number concentration of fine particles measured by P-Trak (1/cm^3)	12,628	10,579 – 15,074
Number concentration of course particles measured by ARTI (1/cm^3)	1,267	943 – 1,702

Table 2.

Arithmetic means (standard deviations) of wind speed and wind index per season.

Season	Wind Speed, mph	Wind Index			p-value for the difference in wind index between sites
		Site 1	Site 2	Site 3	
Summer	5.82 (1.89)	0.56 (0.39)	0.59 (0.34)	0.33 (0.20)	0.006
Fall	8.28 (3.23)	0.50 (0.39)	0.50 (0.38)	0.54 (0.26)	0.872
Winter	9.42 (3.58)	0.66 (0.35)	0.65 (0.35)	0.52 (0.35)	0.152
p-value for the difference between seasons	<0.001	0.695	0.636	0.426	

Table 3.

Comparison of particle concentrations between sites by ANOVA Mixed Model for Fixed Effects. Significant differences between pair-wise comparisons are bolded (α=0.05). Model is adjusted for wind speed and wind index.

Site comparison	Differences of Least Squares Means of natural log transformed concentration values (p-value)				
	EC	OC	EC/OC	Fine particle concentration (P-Trak)	Course particle concentration (ARTI)
1 vs. 2	**0.278 (<0.001)**	**0.197 (<0.001)**	**0.085 (0.016)**	**0.370 (0.007)**	−0.032 (0.866)
1 vs. 3	**1.052 (<0.001)**	**0.502 (<0.001)**	**0.559 (<0.001)**	**0.971 (<0.001)**	−0.191 (0.677)
2 vs. 3	**0.774 (<0.001)**	**0.306 (<0.001)**	**0.474 (<0.001)**	**0.601 (0.002)**	−0.159 (0.712)

Table 4.

Comparison of particle concentrations between seasons by ANOVA Mixed Model for Fixed Effects. Significant differences between pair-wise comparisons are bolded (α=0.05). Model is adjusted for wind speed and wind index.

Seasons	Differences of Least Squares Means of natural log transformed concentration values (p-value)					
	PM2.5	EC	OC	EC/OC	Fine particle concentration (P-Trak)	Course particle concentration (ARTI)
Summer vs. Fall	0.250 (0.352)	−0.473 (0.056)	−0.084 (0.841)	**−0.364 (0.031)**	**−0.610 (0.025)**	−0.404 (0.811)
Summer vs. Winter	−0.210 (0.498)	0.168 (0.696)	−0.161 (0.558)	0.333 (0.065)	−0.854 (0.051)	−0.529 (0.785)
Fall vs. Winter	**−0.460 (0.027)**	**0.641 (0.004)**	−0.077 (0.849)	**0.697 (<0.001)**	−0.244 (0.690)	−0.125 (0.967)