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Spatial Variation of PM_{2.5} Indoors and Outdoors: Results from 261 Regulatory Monitors Compared to 14,000 Low-Cost Monitors in Three Western States over 4.7 Years

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Abstract: Spatial variation of indoor and outdoor PM_{2.5} within three states for a 5-year period is studied using regulatory and low-cost PurpleAir monitors. Most of these data were collected in an earlier study [1] investigating the relative contribution of indoor-generated and outdoor-infiltrated particles to indoor exposures. About 260 regulatory monitors and ~10,000 outdoor and ~4,000 indoor PurpleAir monitors are included. Daily mean PM_{2.5} concentrations, correlations, and coefficients of divergence (COD) are calculated for pairs of monitors at distances ranging from 0 (collocated) to 200 km. We use a transparent and reproducible open algorithm that avoids use of the proprietary algorithms provided by the manufacturer of the sensors in PurpleAir PA-I and PA-II monitors. The algorithm is available on the PurpleAir API website under the name "PM_{2.5}_alt". This algorithm is validated using several hundred pairs of regulatory and PurpleAir monitors separated by up to 0.5 km. The PM_{2.5} spatial variation outdoors is homogeneous with high correlations to at least 10 km, as shown by the COD index under 0.2. There is also a steady improvement in outdoor PM_{2.5} concentrations with increasing distance from the regulatory monitors. The spatial variation of indoor PM_{2.5} indoors is not homogeneous even at distances <100 m. We document substantial differences between Federal Reference Methods (FRM) and Federal Equivalent Methods (FEM).

Keywords: spatial variation; PM_{2.5}; PurpleAir; PM_{2.5}_alt; coefficient of divergence; FEM; FRM; low-cost monitors

1. Introduction

The spatial variation of airborne fine particles (e.g., PM_{2.5}) has long been an interest of environmental regulatory agencies. This interest is due to the sparse nature of the monitoring networks, with monitors separated by scores or hundreds of miles. If the particle levels in the region between monitors are spatially homogeneous, then the monitoring networks would provide reasonable evidence of outdoor concentrations throughout the network area.

A second group deeply interested in spatial variation is health scientists and epidemiologists. They face the same problem of sparse outdoor networks with a need to interpolate or attribute outdoor concentrations to homes or areas with few nearby measurements.

As a result scores of articles on spatial variation have been written by both groups. A nationwide intercomparison of regulatory sites in 27 urban areas in the United States was carried out for the 1999-2000 years [2]. In general, correlations were relatively high, but the authors argued that estimated concentrations could be quite different but still have high correlations. They proposed using coefficients of divergence (COD) as a complementary measure, since the COD is a direct measure of difference in concentration:

$$\text{COD} = \sqrt{\frac{1}{n} \sum_1^n \left(\frac{x_{i1} - x_{i2}}{x_{i1} + x_{i2}} \right)^2} \quad (1)$$

where n is the number of joint measurements made at sites 1 and 2 and the fraction following the summation sign is the difference divided by the sum of the two measurements. The COD is zero if there is perfect agreement between two datasets. It rises to 1 if, for example, one measurement is zero and the corresponding measurement is not zero. The authors reported that both the correlation coefficients and the COD varied more widely than expected, since the measurements made at regulatory sites are considered among the best that can be done, particularly the gravimetric Federal Reference Method (FRM) but also the Federal Equivalent Method (FEM). In the West Coast states, about 33 monitoring sites were included in 6 urban areas, including Seattle, Portland, San Francisco, Los Angeles, Riverside-San Bernadino, and San Diego. With the exception of three outliers, correlation coefficients ranged from 0.57 to 0.99. The COD ranged from 0.11 to 0.26. Since the ranges of both these coefficients were large, the authors concluded that the degree of heterogeneity varied quite widely, and could cause exposure misclassification if homogeneity were assumed.

The natural question arises of what COD value would indicate a homogeneous relationship. That is, how much error should we allow to still assume that a measurement at one site will be a reasonable approximation to a measurement at another site? One study suggested that a 20% error (COD = 0.2) might be a reasonable maximum for considering two sites or methods to be homogenous [3]. A thoughtful major review of 40 studies of PM_{2.5} or PM₁₀ concentrations measured by regulatory monitors in multiple sites (mostly intraurban) adopted this cutoff of 0.2, finding that 16 studies could be considered homogeneous and 24 heterogeneous [4]. For example, three studies found Philadelphia to be homogenous with respect to PM_{2.5} but three other studies found Los Angeles to be heterogeneous. A later complementary review added about 20 studies [5].

Low-cost particle monitors are increasingly being used to measure outdoor air quality. In some areas, they are clustered in such quantities that they can be used to estimate the spatial and temporal variation of PM_{2.5} with increased resolution compared to studies using mainly regulatory monitors. Multiple studies have been carried out using many different low-cost monitors [6-24]. A useful source of information for many of these monitors is the AQ-SPEC program providing laboratory and field comparisons for scores of monitors produced by different manufacturers [25].

One of the better-performing monitors in the AQ-SPEC record was the PurpleAir PA-II monitor containing two Plantower PMS 5003 sensors (<https://www2.purpleair.com/>, <https://www.plantower.com/en/>). PurpleAir has one of the largest networks of monitors operating around the world, and maintains a publicly available database for all monitors. The inclusion of two identical but independent sensors provides a quality control opportunity for every measurement. The existence of the PurpleAir and other low-cost monitor networks has made it possible for the first time to use actual measured data with extreme detailed resolution to determine spatial variation.

In this paper, we first compare the correlations and CODs between PurpleAir monitors and regulatory sites using Federal Equivalent Methods (FEM) or Federal Reference Methods (FRM). The correlations and COD results provide an indication of the quality of the PurpleAir measurements. Second, the correlations and COD results for pairs of PurpleAir indoor and outdoor monitors are calculated. This provides an indication of the replicability of PurpleAir measurements. Finally, the correlations and CODs of pairs of PurpleAir monitors at a range of distances from 100 m to 50 km show the rate of decline of the correlations (or rate of increase for the COD values) with increasing distance apart.

To our knowledge, no long-term (months to years) large-scale (hundreds to thousands of homes) studies of concentrations, correlations and CODs between indoor sites at varying distances apart has been undertaken. This is due mainly to the fact that

these long-term data on indoor particles did not exist until the development of small quiet low-cost monitors that can measure indoor levels over months and years. This lack of indoor data has forced epidemiologists to study only exposure to particles of ambient origin. Their assumption is that nearby homes will all experience about the same exposure to particles of ambient origin. This assumption can now be directly checked using measured PM_{2.5} data from some thousands of PurpleAir monitors. A second assumption (usually unvoiced) is that indoor-generated particles have no effect on human health. Only with this assumption can health effects due to actual exposure to particles from all sources be related to ambient particles alone. Yet health effects can be expected from some indoor-generated particles such as those created by smoking (tobacco, marijuana) and high-temperature cooking.

2. Methods and Materials

A previous study collected publicly available hourly PM_{2.5} data from ~160 regulatory sites and particle number concentrations from ~10,000 outdoor and ~4,000 indoor PurpleAir monitors in the states of Washington, Oregon, and California covering the 4.7-year period from Jan 1, 2017 to September 8, 2021¹. For the PurpleAir sites, PM_{2.5} concentrations were calculated using an improved algorithm based on particle numbers in three size categories as reported by the PurpleAir monitors. This algorithm is completely independent of the two proprietary algorithms provided by Plantower, and has been shown to have reduced bias, improved precision, and a lower Limit of Detection (LOD) [1,8, 26-28]. The algorithm is called ALT-CF3 and is available on the PurpleAir main page as one of 5 “conversion factors” that can be chosen instead of the Plantower proprietary algorithms. The algorithm is also available on the PurpleAir API site, where it is called “PM_{2.5}_alt” (<https://api.purpleair.com/>). A calibration factor of 3.4 was found for both the Plantower 1003 and 5003 monitors used in PA-I and PA-II monitors, respectively²⁷.

2.1. Comparisons with regulatory sites

All PurpleAir sites were matched with FEM/FRM regulatory sites within 50 km distance. At least 30 days with valid daily averages for each pair of sites were required. The PurpleAir sites were regressed on the FEM/FRM sites and both Pearson and Spearman correlation coefficients were determined, as well as the mean COD values.

2.2. Intercomparisons of PurpleAir outdoor and indoor sites

All pairs of PurpleAir indoor and outdoor sites within 50 km distance apart were examined, again with a requirement for at least 30 days of joint valid daily means. Because of the very large numbers of paired sites >2 km apart, random samples of 10,000 pairs of sites between 2 and 50 km apart were selected.

2.3. Intercomparison of regulatory sites

The regulatory sites operate two types of monitors employing gravimetric Federal Reference Methods (FRM) and continuous Federal Equivalent Methods (FEM). In theory, the FEM monitors should be equivalent to the FRM monitors. For collocated monitors we compared FRM-FRM, FEM-FEM, and FEM-FRM pairs to test whether the FEM monitors are capable of matching the gravimetric FRM monitors under field conditions.

3. Results

3.1. Comparisons with regulatory sites

There were 82,562 pairs of PurpleAir and regulatory sites within 50 km apart (Table 1). The mean number of days per matched pair was 304 (about 10 months). A total of 25,113,076 matched days were considered. For distances apart up to 0.5 km, the PM_{2.5} means reported by the Federal regulatory and PurpleAir monitors using the ALT-CF3 algorithm agreed to within 2%. The Pearson correlation coefficient declined slowly from

0.91 at 100 m distance to 0.81 at 20 km distance. The coefficient of divergence increased from 0.24 at 100 m to 0.32 at 50 km.

Table 1. PM_{2.5} concentrations, correlations and coefficients of divergence as a function of distance from regulatory monitors for outdoor PurpleAir monitors in three West Coast states between 1/1/2017 and 9/8/2021.

distance category (km)	# site pairs	mean days per site	FRM FEM mean PM _{2.5} (SE)	PurpleAir mean PM _{2.5} (SE)	Pearson corr. coeff. (r _p) (SE)	Coeff. of divergence (COD) (SE)
<0.1	314	338 (21)	11.7 (0.24)	11.5 (0.30)	0.91 (0.006)	0.24 (0.004)
0.1 to 0.5	42	247 (35)	10.6 (0.64)	10.7 (0.76)	0.90 (0.018)	0.24 (0.014)
0.5 to 1	84	316 (28)	9.6 (0.34)	9.3 (0.45)	0.87 (0.014)	0.26(0.008)
1 to 2	399	313 (13)	10.0 (0.16)	9.4 (0.19)	0.87 (0.007)	0.27 (0.004)
2 to 5	2339	301 (5.0)	10.3 (0.07)	9.7(0.09)	0.87 (0.003)	0.27 (0.002)
5 to 10	5291	297 (3.6)	10.4 (0.04)	9.5 (0.06)	0.85 (0.002)	0.28 (0.001)
10 to 20	14721	301 (2.2)	10.4 (0.02)	9.1 (0.03)	0.81 (0.001)	0.30 (0.001)
20 to 50	59372	305 (1.0)	10.3 (0.01)	9.0 (0.02)	0.76 (0.001)	0.32 (0.000)

As the distance between the PurpleAir and regulatory monitors increased, the PM_{2.5} concentration declined (i.e., the air quality improved) (Figure 1). The improvement was already noticeable at distances from 0.5-1 km. The difference was significant for all distances >1 km from the regulatory monitor.

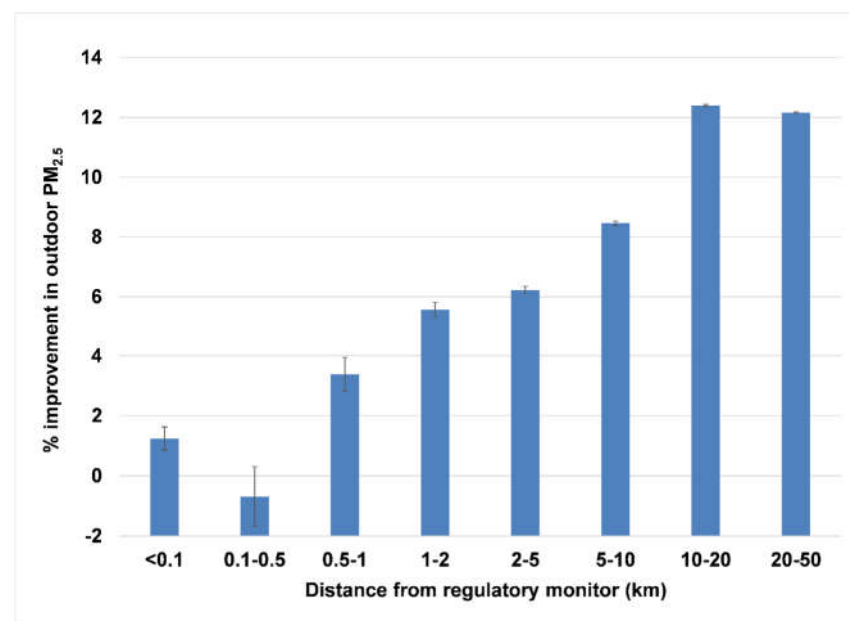


Figure 1. Improvement in outdoor PM_{2.5} with distance from the regulatory monitors.

3.2. Comparison of indoor and outdoor PurpleAir sites

Random samples of 10,000 pairs of outdoor PurpleAir sites and indoor sites at six rings of increasing distances apart from 0 to 50 km were selected. About 75,000 pairs of outdoor and indoor sites met the requirement of at least 30 days of joint measurements by each monitor. The outdoor sites showed mean and median correlations from 0.88-0.99 up to 10 km distance apart. The COD estimates were <0.2 out to 10 km.

By contrast, the indoor sites had Spearman and Pearson correlations of 0.44-0.55 at the smallest distance apart of 0-1 km. R² values ranged from 21% at the smallest distance apart down to 13-14% at the largest distance. The COD mean and median values at all distances ranged only from 0.38-0.43.

Spearman and Pearson correlations, R^2 values, and coefficients of divergence for outdoor and indoor $PM_{2.5}$ are shown (Table 2).

Table 2. Correlations and coefficients of divergence as a function of distance apart for outdoor and indoor pairs of PurpleAir monitors in three West Coast states between 1/1/2017 and 9/8/2021.

Distance	N pairs	Mean				Median			
		rs*	rp*	R ²	CoD	rs	rp	R ²	CoD
Outdoor									
0-1 km	6925	0.93	0.93	0.87	0.14	0.97	0.99	0.98	0.11
1-2 km	7740	0.91	0.92	0.84	0.16	0.96	0.98	0.96	0.13
2-5 km	7544	0.90	0.91	0.82	0.18	0.94	0.97	0.94	0.15
5-10 km	7591	0.88	0.89	0.79	0.20	0.92	0.95	0.89	0.18
10-20 km	7527	0.84	0.85	0.72	0.23	0.88	0.91	0.83	0.21
20-50 km	7639	0.79	0.80	0.65	0.26	0.83	0.86	0.74	0.24
Indoor									
0-1 km	7480	0.53	0.45	0.21	0.40	0.55	0.44	0.19	0.38
1-2 km	7332	0.51	0.42	0.18	0.41	0.53	0.41	0.17	0.39
2-5 km	7424	0.50	0.41	0.17	0.42	0.52	0.40	0.16	0.39
5-10 km	7537	0.48	0.40	0.16	0.42	0.50	0.38	0.15	0.40
10-20 km	7508	0.47	0.38	0.15	0.42	0.49	0.37	0.14	0.40
20-50 km	7589	0.45	0.37	0.14	0.43	0.47	0.35	0.13	0.40

* r_s = Spearman correlation coefficient; r_p = Pearson correlation coefficient

The mean correlations for the outdoor monitors are contrasted with those for the indoor monitors (Figure 2).

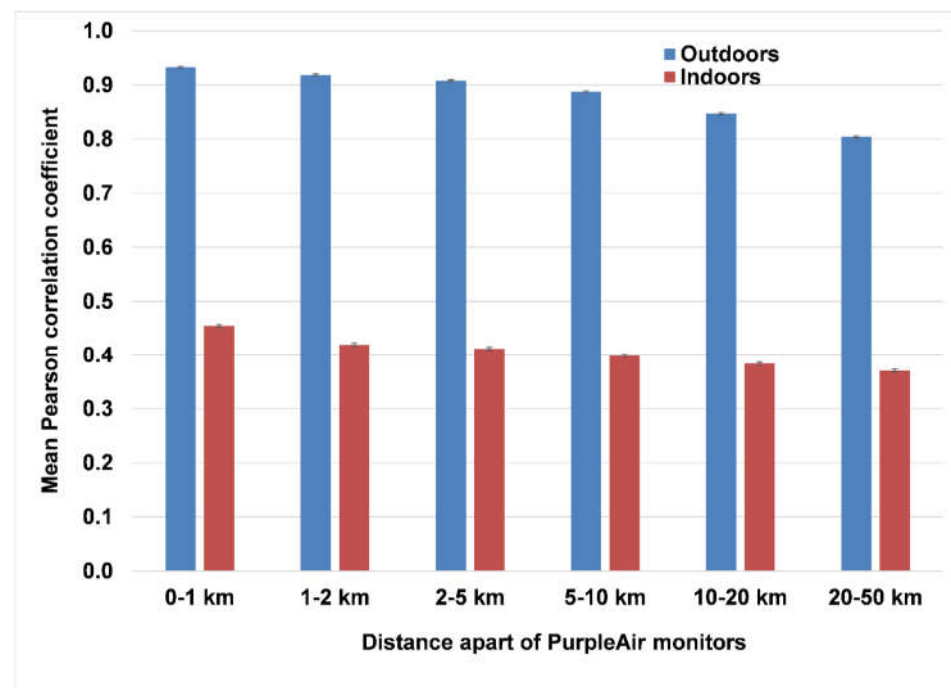


Figure 2. Pearson correlation coefficients as a function of distance for outdoor PurpleAir monitors (blue) and indoor PurpleAir monitors (red).

3.3. Intercomparison of regulatory (FRM/FEM) sites

There were 175 unique regulatory sites operating between 2017 and 2021 in the three West coast states. At each distance category > 0 , ~600 days of joint monitoring were observed, for a total of 3,710,522 days. Two more rings were added (50-100 km and 100-

200 km) in recognition that these measurements were expected to be the best available and might be correlated over longer distances than the 50 km maximum chosen for the PurpleAir monitors. Mean Pearson correlations ranged from 0.93 for collocated monitors down to 0.77 (still moderately correlated) at 50 km. However, at 100 and 200 km, the correlations dropped to 0.63 and 0.52 (R^2 only 41% and 27%), so 50 km may be an upper limit for reasonable correlations to be found. The mean and median CODs were very similar, ranging from 0.13 or 0.14 for the collocated monitors to 0.18 at 20 km, suggesting that 20 km might be considered a cutoff limit for homogeneity.

Table 3. Correlations and coefficients of divergence as a function of distance apart for regulatory monitors in three West Coast states over 5 years (1/1/2017 to 12/31/2021).

Distance (km)	N pairs	Mean				Median			
		r_s^*	r_p^*	R^2	CoD	r_s^*	r_p^*	R^2	CoD
0 (collocated)	68	0.97	0.93	0.93	0.14	0.99	0.95	0.97	0.13
2 to 5	40	0.92	0.85	0.84	0.19	0.95	0.87	0.90	0.19
5 to 10	56	0.91	0.86	0.83	0.17	0.95	0.92	0.90	0.14
10 to 20	134	0.88	0.86	0.78	0.18	0.90	0.87	0.82	0.18
20 to 50	614	0.80	0.77	0.64	0.24	0.84	0.79	0.70	0.23
50 to 100	1316	0.64	0.63	0.41	0.30	0.69	0.67	0.48	0.29
100 to 200	3536	0.52	0.52	0.27	0.34	0.54	0.56	0.29	0.33

* r_s = Spearman correlation coefficient; r_p = Pearson correlation coefficient

3.4. Comparison of FEM and FRM monitors at collocated sites.

There were 68 pairs of collocated instruments adding up to 25,147 days with matched measurements. Correlations and CODs of collocated instruments using matched methods (FRM-FRM, FRM-FEM, and FEM-FEM) are provided (Table 4). The better performance of the gravimetric method is indicated by the R^2 values of 0.96 and 0.99 for the matched FRM monitors compared to 0.82 and 0.88 for the matched FEM monitors. The COD results also favor the FRM-FRM pairs (<0.1) over the FEM-FEM pairs (<0.15), but even the latter meet the requirement for homogeneity (COD<0.2).

Table 4. Comparison of FRM and FEM methods over the 5-year period (2017-2021)..

	# pairs	# days	Mean				Median			
			r_s^*	r_p^*	R^2	CoD	r_s^*	r_p^*	R^2	CoD
FRM-FRM	23	223	0.96	0.98	0.96	0.10	0.98	0.99	0.99	0.08
FRM-FEM	36	470	0.92	0.96	0.92	0.16	0.94	0.98	0.96	0.13
FEM-FEM	9	345	0.90	0.91	0.82	0.15	0.94	0.94	0.88	0.11

* r_s = Spearman correlation coefficient; r_p = Pearson correlation coefficient

4. Discussion.

4.1. Comparisons of PurpleAir with regulatory sites

There was excellent agreement (to within 2%) between regulatory and PurpleAir monitor estimates of $PM_{2.5}$ for distances of 0-0.5 km. This result supports the previous calibrations using this algorithm^{1,26-28}. The PurpleAir mean $PM_{2.5}$ decreases somewhat with increasing distance from the regulatory sites, reaching about 13% lower than the regulatory monitors. This is expected, since most residences are located away from the center city and other areas with expected higher emissions (e.g., busy roadways). The higher incomes associated with homeowners using PurpleAir monitors would also allow living in areas with better environmental surroundings [15]. However, the increasing difference between regulatory and PurpleAir measurements with distance directly affects COD values, even though we believe both measurements are correct. The COD values

may be misleadingly high if the monitors of one type are located in areas that have different concentrations than those with monitors of the second type.

4.2. Intercomparisons of PurpleAir outdoor sites

PurpleAir outdoor sites showed very high agreement, with median Pearson correlations at 100 m at an extraordinarily high level of 0.998, falling only to 0.964 at 20 km distance. This indicates a high degree of dependability and replicability of the sensors. Although this dataset does not include a census of all available matched pairs, two independent random samples were taken, with variations of mean concentrations and correlations at the 0.1-1% level; therefore the findings seem robust.

The period covered included all major fires in a 4.7-year period with very high PM_{2.5} concentrations, as well as periods with widespread rain and resulting PM_{2.5} concentrations near zero. Since there were typically 200-300 days of matched daily means, the results appear robust against extreme variations in PM_{2.5} concentrations.

4.3. Comparisons of PurpleAir indoor sites

These measurements are the first, we believe, for multiple homes with typically hundreds of days of measurements. Indoor Pearson correlations were much lower (about half) than outdoor correlations at comparable distances apart. It has been shown¹ that indoor-generated particles contributed on average about half of the total indoor air concentration, so the reduction (also by about half) of the correlation coefficients clearly reflects the lack of our ability to predict indoor exposures by using only ambient measurements. Indoor-generated particles are often considered to be independent of outdoor concentrations [29], and these low correlations support that idea.

The COD mean values for indoor particle pairs are sharply higher (0.45 to 0.37) than those for the outdoor particle pairs (0.14 to 0.26). If we take 0.20 as the upper boundary for relative homogeneity, then the distance for homogeneity of outdoor particle concentrations would extend to about 10 km. But for indoor concentrations, there is no homogeneity even within 1 km distance.

4.4. Intercomparison of regulatory sites

The 68 regulatory sites with collocated monitors showed excellent performance by the FRM monitor pairs (99% R²) but lower values for the FEM monitor pairs (82-88%). More than 100 3-year studies of collocated FRM and FEM monitors have been carried out by the EPA(<https://www.epa.gov/outdoor-air-quality-data/pm25-continuous-monitor-comparability-assessments>). A considerable fraction of these studies showed disagreement >20% between the methods. This field performance by FEM monitors suggests a need for improved quality assurance at EPA regulatory sites.

5. Conclusions

For 356 PurpleAir sites within 0.5 km of regulatory sites, PM_{2.5} mean concentrations agreed with FEM/FRM measurements to within 2%. This result appears to validate the algorithm and calibration factor of 3.4 used here for all PurpleAir monitors.

Outdoor PM_{2.5} fell almost monotonically with increasing distance from the regulatory monitors, reaching 12- 13% improvement at distances >10 km. This can be considered a yardstick for measuring quantitative change in fine-particle pollution with distance from center-city locations.

Outdoor mean PM_{2.5} concentrations were highly correlated, with evidence of homogeneity (COD<0.2) out to distances of 10 km. Indoor concentrations were poorly correlated and heterogenous (COD>0.2) at all distances. Correlations were about half those for outdoor pairs of monitors, possibly reflecting the finding in a previous study [1] that indoor-generated particles contributed about half of the total potential indoor PM_{2.5} exposure. We conclude that indoor PM_{2.5} exposures cannot be estimated quantitatively from outdoor measurements.

Finally, our analysis of 68 collocated regulatory monitors over 5 years shows high correlations and good COD values for FRM-FRM pairs, with somewhat lower correlations and slightly worse but still good (i.e., <0.2) COD values for FEM-FEM pairs.

Author Contributions: Conceptualization, L.W.; Methodology, L.W. and T.Z.; Software, L.W. and T.Z.; Validation, L.W. and T.Z.; L.W. and T.Z.; Investigation L.W. and T.Z.; Resources, L.W. ; Data Curation, L.W. and T.Z.; Writing – Original Draft Preparation, L.W.; Writing – Review & Editing, L.W. and T.Z.; Visualization, L.W. ; Supervision, L.W. ; Project Administration, L.W.; Funding Acquisition, Not Applicable.

Funding: This research received no external funding.

Institutional Review Board Statement: “Not applicable” for studies not involving humans or animals.

Data Availability Statement: All raw data publicly available from PurpleAir websites (<https://www2.purpleair.com/>), (<https://api.purpleair.com/>). All analyzed data available on request from the corresponding author.

Acknowledgments: We acknowledge the contribution to science made by the PurpleAir organization in making all public data available on the Internet.

Conflicts of Interest: The authors declare no conflict of interest.

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