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FINE-SCALE PM_1 POLLUTION DYNAMICS IN AN URBAN–SUBURBAN ENVIRONMENT

Research paper

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Abstract: Submicron particulate matter (PM_1) is not routinely regulated as a separate ambient-air fraction, yet its spatial behavior can provide useful information on combustion-related aerosol and neighborhood-scale exposure contrasts. This study examined one complete heating/non-heating cycle (16 April 2024-15 April 2025) at five monitoring locations in the Novi Sad urban-suburban system, Serbia: Novi Sad, Sremska Kamenica, Sremski Karlovci, Ledinci and Beočin. Daily PM_1 observations from a community sensor network were evaluated using descriptive statistics, seasonal contrasts, inter-site correlations and a parsimonious cross-site regression model. Median PM_1 concentrations over the study window ranged from 8 to 14 μg m^{-3}. Heating-season medians were 2.2–3.2times higher than non-heating medians, with the largest absolute winter burden observed in Novi Sad. Daily concentrations were strongly correlated across the suburban sites (r = 0.80-0.90 for most pairs), indicating coherent regional forcing, while the weaker association between Novi Sad and Beočin (r = 0.66) pointed to local modulation. A linear model using the four surrounding sites reproduced daily PM_1 at the urban site with R^2 = 0.72 on a chronologically independent test period. The combined results show that a compact five-site network can resolve both shared pollution episodes and site-specific amplification without requiring a geographically extensive monitoring design.

Key words: PM_1, submicron particles, urban-suburban gradient, low-cost sensors, seasonal variability

INTRODUCTION

Ambient particulate matter remains a major environmental determinant of population health. Current air-quality regulation and health-based guidance are centered on $PM_{2.5}$ and PM_{10}, while PM_1 is generally not treated as a separate regulatory mass fraction. Nevertheless, particles below 1 μm account for an important component of combustion-derived and secondary aerosol, and their temporal behavior may differ from that of the coarser particle fractions. The World Health Organization (2021) therefore provides a useful health context for particulate pollution as a whole, but it does not define a specific ambient guideline value for PM_1.

European observations indicate that submicron aerosol is strongly seasonal. In a Central European urban area, Samek et al. (2018) reported daily mean PM_1 concentrations of 6.9 μg m^{-3} in summer and 17.3 μg m^{-3} in winter, with combustion and secondary aerosol making larger contributions during the cold season. Long-term measurements in Warsaw likewise demonstrated pronounced seasonal changes in PM_1 concentration and composition (Majewski et al., 2018). Such evidence is particularly relevant to continental urban areas where residential heating coincides with weak winter dispersion.

A second difficulty is spatial representativeness. Regulatory stations provide high-quality measurements but cannot resolve every neighborhood-scale gradient. Low-cost optical sensors can complement reference networks by increasing spatial density, provided that their limitations are recognized. Plantower sensors have shown good ability to track temporal PM variability, but their response can vary with season, humidity, aerosol type and sensor age (Sayahi et al., 2019). Laboratory and field evaluations have also shown that Plantower performance depends on particle size and relative humidity (Zamora et al., 2019).

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Consequently, dense sensor networks are most defensible when used for comparative patterns and screening rather than as substitutes for regulatory measurements.
The present study focuses on a deliberately compact urban-suburban transect rather than the full regional monitoring network. Five locations were selected around Novi Sad to test whether a one-year record is sufficient to resolve seasonal amplification, spatial coherence and local departures within a geographically compact system. The objective was to quantify (i) site-level PM_1 distributions, (ii) heating versus non-heating differences, (iii) inter-site correlation structure and (iv) the extent to which daily PM_1 at the urban site can be reconstructed from simultaneous observations at four surrounding locations. This scope provides a focused assessment of fine-scale dynamics without attempting source apportionment or long-term trend attribution.

MATERIAL AND METHODS

Study area and monitoring design

The study domain comprised Novi Sad (D1) and four surrounding settlements: Sremska Kamenica (D2), Sremski Karlovci (D3), Ledinci (D4) and Beočin (D5). The five sites form a compact urban-suburban system within the wider Novi Sad area and represent different combinations of urban density, traffic, residential heating and local land use. Restricting the analysis to these locations was intentional: the objective was to examine short-range spatial coherence around the urban center rather than to characterize the entire regional network.
PM data were obtained from the Klimerko community monitoring network, which uses Plantower PMS7003 optical particle sensors. The devices report PM_1, $PM_{2.5}$and PM_{10}, but only PM_1 was used here. The measurements were treated as indicative, comparative observations. No claim of regulatory equivalence was made, consistent with published evaluations showing that low-cost optical PM sensors require careful interpretation under varying aerosol and meteorological conditions (Sayahi et al., 2019; Zamora et al., 2019).

Study period, preprocessing and seasonal definition

The analytical window extended from 16 April 2024 through 15 April 2025 and therefore contained one complete non-heating period and one complete heating season. The heating season was defined as 15 October-15 April and the non-heating period as 16 April-14 October. Daily observations were analyzed as provided in the research dataset; missing days were not interpolated. Valid PM_1 coverage was 364 days at D1, 358 at D2, 356 at D3, 327 at D4 and 335 at D5. The shorter record at D5 ended on 21 March 2025 and this limitation was considered when interpreting the seasonal comparison.

Statistical analysis and cross-site model

For each site, the number of valid days, arithmetic mean, median, 95th percentile (P95), maximum and seasonal medians were calculated. Pearson correlation coefficients were computed from pairwise-overlapping daily observations and displayed as a correlation heatmap. Because the distributions were right-skewed and episodic, the median and P95 were emphasized in the descriptive interpretation.
A simple linear regression was used as an exploratory test of network coherence. Daily PM_1 at Novi Sad (D1) was modeled from simultaneous PM_1 observations at D2-D5. Only dates with complete observations at all five sites were used (n = 299). To avoid evaluating the model on the same days used for fitting, the data were ordered chronologically: the first 70% (n = 209) formed the training period and the final 30% (n = 90) formed an independent test period. Performance was summarized by R^2, root mean square error (RMSE) and mean absolute error (MAE). The model was not intended as a forecasting system or source model; it was used only to quantify how much of the urban day-to-day variability was shared with the surrounding network.

RESULTS AND DISCUSSION

Spatial distribution of PM_1

PM_1 concentrations differed across the five sites despite their relatively short geographic separation (Table 1). The annual-window median was highest in Novi Sad (14 μg m^{-3}) and lowest at Sremska Kamenica, Sremski Karlovci, Ledinci and Beočin (8 μg m^{-3} at each site). The contrast became more pronounced toward the upper tail: D1 reached a P95 of 38.8 μg m^{-3}, compared with 29.1-33.0 μg m^{-3} at the surrounding sites. This indicates that the urban location differed not only in central tendency but also in the magnitude of high-concentration days.

Table 1. *Descriptive PM_1 statistics and seasonal medians for the five monitoring sites.*

Site	N	Mean	Median	P95	Max	NH med.	H med.	H/NH
D1	364	16.9	14.0	38.8	57	10.0	22.0	2.20
D2	358	11.2	8.0	29.1	53	6.0	14.0	2.33
D3	356	11.8	9.0	33.0	45	5.0	16.0	3.20
D4	327	11.9	9.0	32.0	54	5.0	15.0	3.00
D5	335	12.0	9.0	29.3	62	6.0	16.0	2.67

Concentrations in μg m^{-3}; NH = non-heating period; H = heating season.

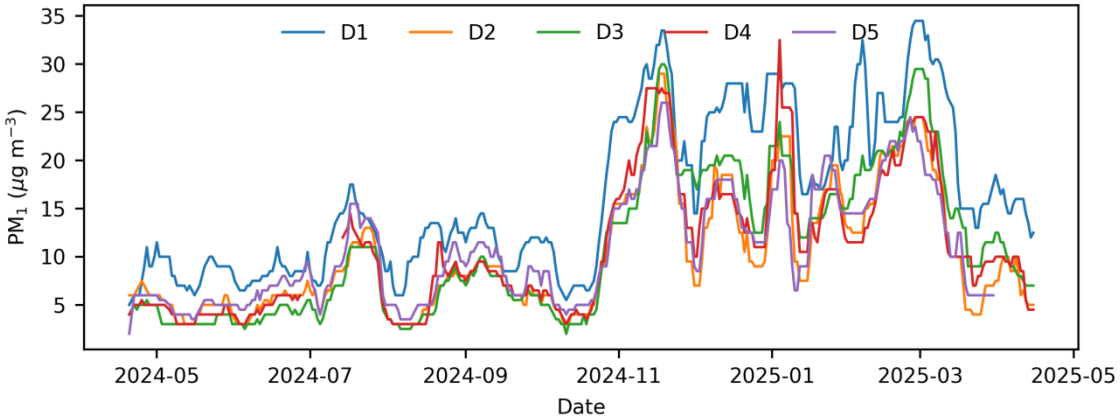


Fig. 1. *Fourteen-day rolling median PM_1 concentrations at the five monitoring sites during the study period. Gaps represent missing observations.*

The temporal profiles in Figure 1 show a common seasonal envelope, with lower concentrations during the warm period and repeated increases during winter. The broad synchrony is consistent with the role of regional meteorology in controlling dispersion and accumulation. At the same time, the amplitude of individual episodes was not identical among sites, indicating that common atmospheric forcing was superimposed on local differences in emission intensity and site surroundings. Comparable cold-season enhancement has been reported in Central European PM_1 studies; Samek et al. (2018), for example, observed a winter/summer mean ratio of approximately 2.5 in an urban Polish setting. The magnitude in the present dataset was site-dependent rather than uniform, which is expected where heating structure and local source density vary over short distances.

Inter-site correlation structure

Daily PM_1 concentrations were positively correlated throughout the network (Figure 2). The strongest relationships occurred among several suburban pairs, including D2-D4 (r = 0.90), D2-D5 (r = 0.88) and D3-D4 (r = 0.86). Novi Sad was most strongly associated with Sremski

Karlovci (D1-D3, r = 0.90), whereas its correlation with Beočin was lower (D1-D5, r = 0.66). The generally high correlations indicate that major concentration changes were not purely local events. Rather, the five sites responded to a shared regional component, while the variation in r values indicates differing local modulation.

This interpretation is compatible with the behavior expected in compact urban sensor networks: common meteorological conditions can synchronize temporal variability, whereas traffic, domestic heating and other local sources modify concentration amplitude. Dense low-cost networks are particularly useful for resolving this combination of regional coherence and local heterogeneity, although sensor-specific uncertainty remains important (Sayahi et al., 2019).

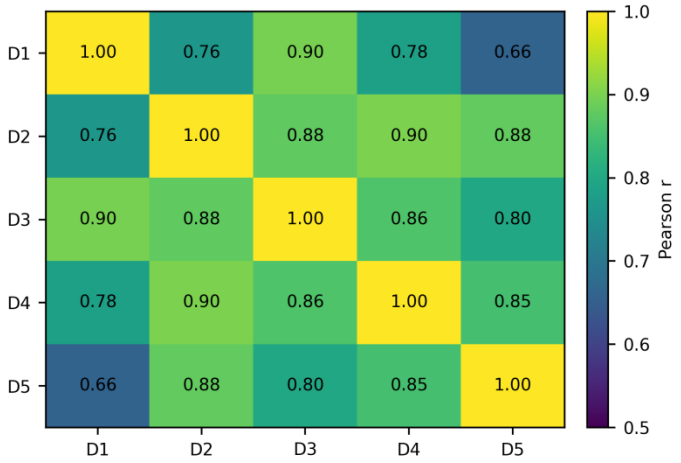


Fig. 2. *Pearson correlation matrix for daily PM_1 concentrations. Coefficients are based on pairwise-overlapping observations.*

Heating-season amplification

All five locations showed higher median PM_1 during the heating season (Figure 3). The heating/non-heating median ratios were D1: 2.20, D2: 2.33, D3: 3.20, D4: 3.00, D5: 2.67. The strongest relative amplification occurred at Sremski Karlovci, while Novi Sad retained the highest absolute heating-season median (22.0 μg m^{-3}). These results support a spatially widespread cold-season effect rather than an isolated urban-core phenomenon.

The seasonal contrast should not be attributed to residential heating alone. Heating activity increases during the same period in which lower mixing heights, calm conditions and temperature inversions favor particle accumulation; secondary aerosol formation and regional transport can also contribute. The Central European source-apportionment study of Samek et al. (2018) similarly found that both combustion and secondary aerosol contributions to PM_1 increased in winter. The present analysis does not contain chemical tracers and therefore identifies seasonal amplification rather than its causal partitioning.

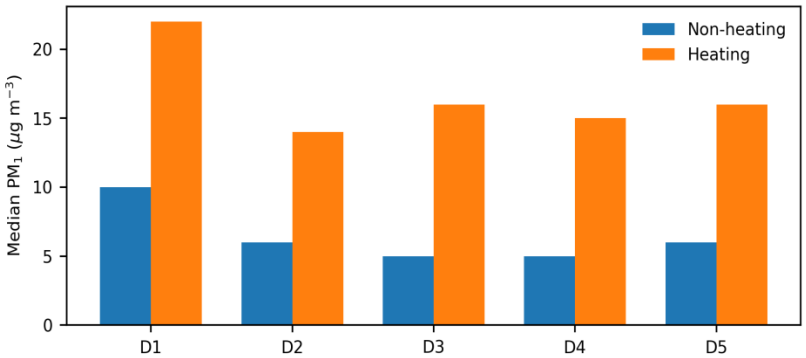


Fig. 3. *Median PM_1 concentrations during the non-heating and heating periods at the five sites.*

Cross-site reconstruction of urban PM_1

The exploratory cross-site model reproduced a substantial part of the day-to-day PM_1 variability at Novi Sad. On the independent final 30% of the complete-case record, the model achieved $R^2 = 0.72$, RMSE = 6.4 μg m^{-3} and MAE = 4.7 μg m^{-3} (Figure 4). This level of performance is notable because the model used no meteorological variables and no measurements from the target site as predictors. It therefore provides an additional quantitative indication that much of the temporal signal was shared across the compact monitoring domain.
The model should not be interpreted as a calibrated prediction tool. Its coefficients are conditional on one year, one sensor network and the selected locations; multicollinearity among the surrounding sites also limits physical interpretation of individual regression coefficients. A stronger predictive framework would require meteorological covariates, longer temporal validation and explicit sensor calibration. Here, the regression serves a narrower purpose: it demonstrates that the urban signal contains a strong network-wide component while leaving a residual fraction attributable to local processes, measurement uncertainty and unmodeled atmospheric effects.

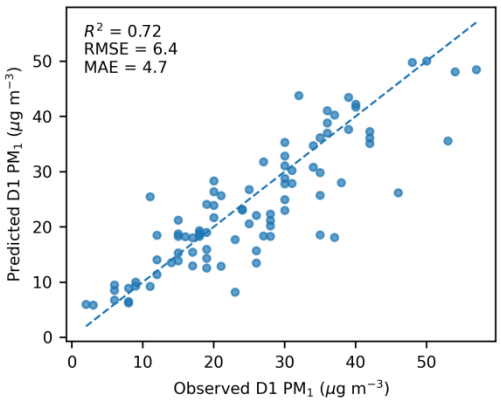


Figure 4. *Observed and regression-predicted daily PM_1 at Novi Sad (D1) for the chronologically independent test period.*

Limitations and implications

Three limitations are particularly relevant. First, optical low-cost sensors can be affected by humidity, aerosol composition and sensor aging. Sayahi et al. (2019) documented seasonal differences and drift in Plantower sensors, while Zamora et al. (2019) found particle-size- and humidity-dependent accuracy. Second, the five records were not perfectly complete, especially at Ledinci and Beočin, although no gap filling was used. Third, the study did not include chemical composition or source tracers and therefore cannot distinguish residential combustion from traffic, secondary aerosol or transported pollution. These limitations argue for conservative interpretation of absolute concentrations, but they do not negate the value of the network for comparing observed temporal and spatial patterns.
From a monitoring perspective, the five-site design appears sufficient to demonstrate fine-scale structure around Novi Sad without extending the analysis to the full regional network. This is important methodologically: a compact network can identify shared pollution episodes, quantify urban-suburban contrasts and flag locations or periods that warrant more intensive reference-grade measurements. The present results therefore support a tiered monitoring strategy in which dense indicative sensing is used for spatial screening and targeted deployment, while regulatory and source-specific conclusions remain anchored to reference instrumentation and dedicated chemical analyses.

CONCLUSION

One complete heating/non-heating cycle across Novi Sad and four nearby settlements revealed a coherent but spatially non-uniform PM_1 field. Median concentrations were highest at the urban site, all locations showed cold-season amplification, and daily concentrations were strongly correlated across the network. The correlation structure and the cross-site regression both indicate a substantial shared regional component, whereas differences in episode magnitude and weaker correlations for selected pairs point to local modulation. A five-site urban-suburban design therefore provides sufficient spatial resolution for a focused conference-level assessment while avoiding unnecessary use of the broader multi-year regional dataset. The results should be interpreted as comparative and indicative because the measurements originate from low-cost optical sensors and no source-apportionment data were available.

ACKNOWLEDGEMENTS

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