

Investigating the relationship between PM₁₀ and climatic parameters using GAM model: a case study of Skopje, Kumanovo, Bitola, North Macedonia

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Abstract: This study applies Generalized Additive Models (GAMs) to investigate the complex non-linear relationship between PM₁₀ concentrations and climate factors in Skopje, Kumanovo and Bitola from 2012 to 2023. The three largest Macedonian cities have continuous challenges with the polluted air, which results from a combination of natural and socio-economic factors. Researches for the climate influences on air pollution are crucial for understanding when and why pollution episodes occur, which in turn informs more effective forecasting, public health warnings, and mitigation strategies. GAMs allow for a flexible, non-linear assessment of how temperature, relative humidity, wind speed, and precipitation influence air pollution concentrations. The analysis showed a consistent and significant negative relationship between temperature and PM₁₀ concentrations, indicating higher pollution levels under colder conditions. Precipitation was generally associated with lower PM₁₀ concentrations, whereas relative humidity was mostly positively associated with PM₁₀, although, these relationships were not statistically significant for all observations. Wind speed showed variable associations with PM₁₀ concentrations, with significant negative relationships observed only at some monitoring locations. These insights emphasize the role of climate forecasting in air quality management and highlight the need for targeted pollution mitigation strategies in North Macedonia.

1. Introduction

Air pollution in cities is a significant environmental issue, driven by the complex interaction between natural factors and human activities, particularly in developing countries (Mayer, 1999; UNEP 2024; Mage et al., 1996). It affects health and influences the development of the economy (Bai et al. 2018). Cities are by nature concentrations of humans, materials and activities. They therefore exhibit both the highest levels of pollution and the largest targets of impact (Fenger, 1999). Urban air quality is influenced by various factors, including socio-economic factors and meteorological factors (Chen et al., 2023). Air pollution is a significant problem in North Macedonian cities and urban centres (World Bank 2019). North Macedonia is considered to have some of the worst air quality in the region, and consequently some of the worst globally (Avis, 2022). Pollution caused by suspended particles is at a high level and is spread all over the urban areas in the country. The average annual values of PM₁₀ exceed the annual limit value in every year since 2005 (Angelevska et al., 2017; Manevska et. al., 2020). One of the most critical substance is PM₁₀, for which the dominant source of emissions is household

heating (Spasovska and Stefanovska, 2018). Air pollution is significantly affected by meteorological conditions (Perez et al., 2020; Aldrin and Haff, 2005; Liu et al., 2020; Khan, 2025), where it has been proven that PM_{10} levels are affected by various atmospheric parameters, such as wind speed and direction, relative humidity, temperature and rainfall (Munir, 2015). The geographical position of the cities also plays a key role in shaping ambient pollution levels in urban areas around the world (Jennifer and McKendry, 2009), where both topographical features and prevailing meteorological conditions exacerbate the degradation of air quality (Martinez et al., 2018). PM_{10} pollution in North Macedonia poses serious health risks, contributing to respiratory, cardiovascular diseases and premature deaths, while also straining the economy through increased healthcare costs and reduced workforce productivity (Manevska et al., 2020; Avis, 2022). Particulate matter (PM) is responsible for over 1350 deaths in North Macedonia annually and thousands of lost work days, representing an economic cost of €253 million annually or 3.2 percent of GDP (World Bank 2014; Meisner et al., 2015). The study has a lot of importance for the national strategies on air pollution, as it provides important insights into the influence of natural and climatic factors on the levels of air pollution. The objective of this research is to investigate the relationship between PM_{10} and climate elements (air temperature, precipitation, wind speed and relative humidity) by using Generalized Additive Models (GAM).

GAM has been proved to be suitable for investigating many environmental issues, of which in a lot of studies the GAM model was used to investigate the non-linear relationship between air pollution and climate parameters (Belušić et al., 2015; Barmpadimos et al., 2011; Pearce et al., 2010; Ma et al., 2020; Yan et al., 2024; Han et al., 2022; Munir, 2015; Ravindra et al., 2019). Generalized additive models (GAMs) have become a standard analytic tool in time-series studies of air pollution and health. GAMs allow non-linear relationships between the independent predictors and response. During the past decade, the following model has become standard in air pollution studies (He et al., 2005). The use of GAM is crucial for examining the complex, non-linear relationship between PM_{10} concentrations and climatic elements. Given that variables such as temperature, precipitation, relative humidity and wind speed exert non-linear effects on air pollution, GAM enables a more accurate representation of these interactions, facilitating a deeper understanding of their influence on particulate matter levels which is important for getting a clearer image of air pollution dynamics and improving air quality management strategies in the largest urban cities in North Macedonia – Skopje, Kumanovo and Bitola.

2. Study Area

The City of Skopje is located in the Skopje Basin, in the northern part of the Republic of North Macedonia (Figure 1), between latitudes $41^{\circ}42'15''N$ and $42^{\circ}16'20''N$, and longitudes $21^{\circ}09'40''E$ and $21^{\circ}49'15''E$ (Greenwich). The basin is geographically framed by several mountain ranges: to the south by the Karadžica and Golešnica massifs, to the east by Mount Gradiška and the Ovče Pole plain, to the north by the Kumanovo Valley and the Skopska Crna Gora massif, and to the west by Mount Žeden, which separates it from the Polog Valley. Within these natural boundaries, the Skopje Basin spans an area of 1,924.2 km², including 343.9 km² of flatland situated at elevations between 150 and 300 meters above sea level (Lazarevska and Markoski, 2019). The capital city of Skopje is the largest urban area in the country, as of the latest census in 2021, Skopje has a population of 526,502 which is 27.7% of the total population of the Republic of North Macedonia (State Statistical Office 2021). The city of Skopje is the main economical and administrative center. Given that the majority of North Macedonia's economic and administrative institutions are concentrated in Skopje, the city experiences substantial internal migration, primarily driven by employment opportunities and higher education pursuits. As a result, there is a continuous demand for new residential buildings and associated infrastructure to accommodate the growing population. Since the city has an

ongoing problem for years with the poor air quality, which is especially challenging during the winter season, with the ongoing urbanization of the city, air purification processes are increasingly hindered. The construction of high-rise buildings within the limited space of the city center further obstructs the natural circulation of wind, which plays a vital role in the natural dispersion and cleansing of air pollutants. Many studies place Skopje as the most polluted capital in Europe during the winter when concentrations of PM_{10} reach hazardous levels which contributes to a higher burden of premature mortality comparing to many European Union countries (Manevska et al., 2025). According to a study conducted by (UNDP 2020), residential heating accounts for approximately 32% of total emissions, followed by industrial activities (20%), road transport (19%), construction (12%), and waste management (7%). Other studies also indicate that household heating is the primary contributor to wintertime air pollution, mainly because many homes rely on inefficient wood-burning stoves and low-quality solid fuels during the winter (Trpevska - Trajkovska and Stefanova 2019; Manevska et al., 2025).

The city of Kumanovo is located in the northeast planning region (Figure 1), one of the eight non-administrative units—statistic regions which arise by grouping the municipalities from lower rank in administrative units in the Republic of North Macedonia. This planning region covers an area of 2,310 km² (Lazarevska and Markoski, 2019). According to the last census, Kumanovo is the second most populated city in North Macedonia with 98,104 inhabitants (State Statistical Office, 2021). Kumanovo also has great geographical position where the traffic corridors 10 and 8 intersect. The openness of the Kumanovo Valley, in the south and to the valley of the Kriva Reka towards Kriva Palanka contributes to the establishment of the connections. The Kumanovo Valley and the mountains of Skopska Crna Gora, Kozjan and Ruen are one of the most distinct relief forms in this region. The plain-hilly land at an elevation of about 300–700 m. dominates in the relief structure (Lazarevska and Markoski, 2019). In Kumanovo, studies identified multiple sources for air pollution but mostly the air pollutants in Kumanovo originate from the usage of firewood as a main heating source followed by coal and oil (Municipality of Kumanovo, 2021).

City of Bitola is located in the south-western part of North Macedonia, (Figure 1), in the central part of Pelagonija Valley, on the two banks of Dragor River, right tributary of the Crna River, on the footslope of Baba Mountain. The city is bounded on the north by the slopes of the Snegovo-Oblakovo Massif and on the south by the Neolica Range. The Pelagonija plain flat area is the eastern border. Bitola itself lies on fluvio-glacial alluvium, at an altitude of 550 to 750 meters, and the western border is the small Caparsko Field in the basin of river Shemnica and Ilinska Mountain. According to the last census (State Statistical Office, 2021) the municipality of Bitola has 85,164 inhabitants.

The high use of solid fuels for household heating, the variety of combustion technologies, and their generally low combustion efficiency make residential combustion processes one of the most important sources of air pollution in Bitola. Therefore, households are significant sources of particulate matter and air pollutant emissions, especially in the heating period. The energy sector also contributes significantly to local and national air pollution in addition to residential heating. One of the main sources of energy is the thermal power plant in the neighboring Municipality of Novaci, REK Bitola, the largest electricity producing facility in North Macedonia. It relies on burning lignite and is a major contributor of particulate matter and other atmospheric pollutants. REK Bitola was estimated to contribute up to 68 % of the national emissions of $PM_{2.5}$ and around 27 % of the national emissions of PM_{10} . Which means that the contribution of these emissions to the ambient air pollution in the Bitola region and nationwide is large (Municipality of Bitola, 2024).

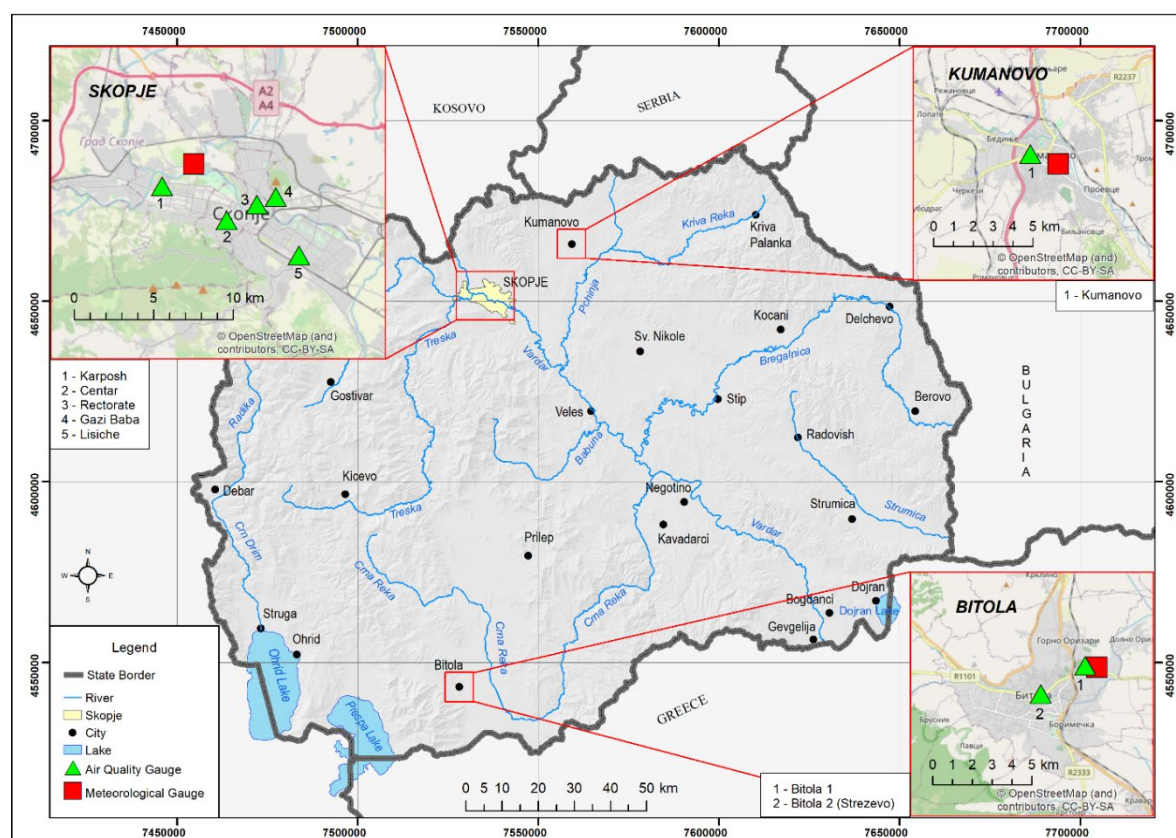


Figure 1. Map of geographical position of the meteorological and air quality gauges in Skopje, Kumanovo and Bitola. Source: Open Street Map, MOEPP 2025

3. Materials and Methods

This study centers on the examination of meteorological data collected over a monthly twelve-year period (2012–2023), with the primary sources being official institutions of the Republic of North Macedonia. The data for the climate parameters (air temperature, precipitation, relative humidity and wind speed) were taken from the meteorological gauges in Skopje, Kumanovo and Bitola – Hydro meteorological service of the Republic of North Macedonia. The data for PM₁₀ was taken from the gauges for air quality of which five are in the territory of Skopje, two in Bitola and one in Kumanovo – Ministry of Environment and Spatial planning of North Macedonia.

In order to explore the non-linear relationships between PM₁₀ concentrations and climate variables, a Generalized Additive Model (GAM) was conducted on the dataset. Firstly, it was determined descriptive statistics on the data, the whole statistical analysis was run on the software “XL-stat” with the “R” addition. Descriptive statistics were employed to summarize, organize, and present the data in a meaningful and concise manner. These statistics include measures of central tendency such as the mean, median, mode, and range. The results of the GAM model are shown with smoothed terms, component plots and the model was tested with goodness of fit test that includes the statistical indicators R², RMSE AIC and the ANOVA analysis. The model was applied separately to the data from each targeted gauge, grouped by city. Since the data for all the parameters was continuous and followed a normal distribution the model was conducted using the normal Gaussian distribution of data (Aldrin and Haff, 2005; Zhang and El-Shaarawi, 2010)

$$y_t = s_1(x_{1t}) + \dots + s_p(x_{pt}) + \varepsilon_t$$

Of which y_t is the pollution variate (PM_{10}), s_1 are the smooth functions that must be estimated and x_{1t} are the predictor variables (climate parameters). ε_t is the residual, error term or the part of y_t that is unexplained by the model. Although previous studies such as (Chaloulakou et al., 2003; Schlink et al., 2003) applied a logarithmic transformation to air pollutant data to address heteroscedasticity and ensure positive predictions, this study models PM_{10} concentrations directly, without transformation. This approach was selected based on the distribution and behavior of the dataset over the twelve-year period.

4. Results

The descriptive statistics for the data collected for 2012 – 2023 categorized by gauges for the cities Skopje, Kumanovo, Bitola is presented on table 1, 2 and 3. This dataset provides meteorological (air temperature, precipitation, relative humidity and wind speed) from the meteorological gauge Zajchev Rid in Skopje and air pollution (PM_{10}) statistics taken from the data of five air quality gauges on the territory of the city of Skopje. The statistics represent that the average temperature is 13.9°C, with a wide range from -4°C to 27.7°C, while precipitation and relative humidity also show significant variability, indicating diverse weather conditions. Wind speed is shown as relatively stable. The concentrations of PM_{10} vary notably by location, with Lisiche recording the highest average and peak values, suggesting that it's most polluted. In contrast, Karposh shows the lowest average PM_{10} levels, indicating relatively better air quality. High standard deviations in PM_{10} across all areas reflect significant daily fluctuations, likely influenced by weather changes such as humidity and rainfall, which can trap or clear pollutants.

Table 1. Descriptive statistics for four climate parameters and PM_{10} for Skopje gauges.

Statistic	Temperature	Precipitation	Relative humidity	Wind speed	Lisiche, PM_{10}	Karposh, PM_{10}	Gazibaba, PM_{10}	Centar, PM_{10}	Rectorate PM_{10}
Nbr. of observations	144	144	144	144	144	144	144	144	144
Minimum	-4.000	0.000	39.000	1.400	22.819	20.888	15.525	23.881	21.683
Maximum	27.700	167.500	88.000	3.500	301.031	225.042	219.380	237.950	225.860
1st Quartile	6.500	21.050	57.000	2.200	36.814	33.121	35.515	35.329	36.953
Median	13.400	37.000	64.000	2.400	55.565	41.805	51.785	44.081	47.478
3rd Quartile	21.325	58.300	75.000	2.700	88.746	62.973	72.666	67.662	76.192
Mean	13.850	43.655	64.903	2.411	74.848	54.749	62.039	57.696	62.627
Variance (n-1)	67.523	1029.626	118.172	0.142	2866.598	1229.576	1559.284	1333.041	1464.805
Standard deviation (n-1)	8.217	32.088	10.871	0.377	53.541	35.065	39.488	36.511	38.273

Source: Compiled by author, 2025

The next (Table 2) shows the descriptive statistics for the data of the city of Kumanovo. On the territory of Kumanovo, one meteorological gauge and one air quality gauge are analyzed.

Table 2. Descriptive statistics for Kumanovo gauge

Statistic	Temperature	Precipitation	Relative humidity	Wind speed	# 12. Kumanovo, PM10
Nbr. of observations	144	144	144	144	144
Minimum	-4.700	0.000	50.000	0.100	15.497
Maximum	27.500	181.100	92.000	3.500	145.851
1st Quartile	6.100	24.075	69.000	1.300	37.423
Median	12.900	41.700	75.500	1.800	45.577
3rd Quartile	20.925	64.050	82.250	2.200	65.477
Mean	13.492	46.601	75.069	1.792	53.373
Variance (n-1)	68.524	1058.472	87.366	0.462	599.977
Standard deviation (n-1)	8.278	32.534	9.347	0.680	24.494

Source: Compiled by author, 2025

Climate parameters indicate moderate average temperature (13.5°C), relatively high humidity (mean 75.1%) and low wind speeds (mean 1.8 m/s) that may lead to pollution accumulation. Precipitation is highly variable (up to 181.1 mm) and may influence the air quality by removing pollutants. Average concentration of PM₁₀ in Kumanovo is 53.37 µg/m³, with a range from 15.5 to 145.9 µg/m³ and a high standard deviation of 24.5, which indicates high daily variation. The moderate median of 45.58 µg/m³ suggests that while there are extreme values, the pollution is generally moderate and may increase with stagnant weather conditions such as low wind or high humidity.

(Table 3) presents the descriptive statistics for the data of one meteorological gauge and two air quality gauges in the city of Bitola.

Table 3. Descriptive statistics for Bitola gauges

Statistic	Temperature	Precipitation	Relative humidity	Wind speed	# 2. Bitola 1 PM10	# 3. Bitola 2 Strezevo, PM10
Nbr. of observations	144	144	144	144	144	144
Minimum	-6.000	0.000	44.000	0.500	14.909	8.325
Maximum	25.900	213.100	87.000	3.200	131.413	259.879
1st Quartile	5.750	27.300	59.000	1.300	30.728	30.992
Median	12.100	50.050	66.000	1.600	37.256	44.345
3rd Quartile	19.650	80.225	76.000	1.825	50.113	60.844
Mean	12.494	55.224	66.688	1.596	43.454	51.704
Variance (n-1)	64.129	1422.575	109.419	0.167	423.003	1049.626
Standard deviation (n-1)	8.008	37.717	10.460	0.409	20.567	32.398

Source: Compiled by author, 2025

Weather conditions are moderate, with an average temperature of 12.5°C, relatively high humidity (mean of 66.7%), and low wind speeds averaging 1.6 m/s. Precipitation ranges from 0.0 mm to 213.1 mm which is the maximum among the compared datasets. The average PM₁₀ levels in Bitola 1 are 43.45 µg/m³ with low variation (SD = 20.57), indicating that the pollution levels are moderate stable. In contrast, the results for Strezevo (Bitola 2) show higher mean PM₁₀ of 51.70 µg/m³ and a wider range, reaching 259.88 µg/m³, with a larger standard deviation (32.40), indicating more significant fluctuations and occasional high pollution events.

The analysis shows significant differences in air quality and climate conditions among Skopje, Kumanovo, and Bitola. Skopje recorded the highest average PM₁₀ concentration (62 µg/m³) and the greatest variability, with peak values reaching 301 µg/m³, indicating substantial pollution likely associated with urban activities and industrial emissions. Although Skopje also had the highest average wind speed (2.41 m/s), which would generally promote pollutant dispersion, the city's basin topography and ongoing urbanization may limit ventilation and reduce the effectiveness of wind in dispersing air pollutants.

Kumanovo has an average PM₁₀ level of 53.37 µg/m³, which is moderate, with less fluctuation and slightly lower average wind speeds (1.79 m/s). Bitola, and especially the results from the station Bitola 1, had the lowest average PM₁₀ (43.45 µg/m³) and the least fluctuations, which means that the air quality was better and more stable. However, the higher peaks of the gauge Bitola 2 (Strezevo) (up to 259.88 µg/m³) indicate the occurrence of high air pollution events.

Overall, Skopje is the most polluted, Kumanovo is moderately affected, and Bitola generally fares better, though localized spikes in Strezevo highlight concerning PM₁₀ concentrations.

After the descriptive statistics and its analysis, the GAM model was applied to the dataset. In Table 4 are shown the smoothed terms.

Table 4. Smoothed terms

Gauge	Variable	edf	F	p-value
Centar	Temperature	5.129	13.478	0
Centar	Precipitation	1.733	7.068	0.001
Centar	Relative Humidity	2.294	5.818	0.001
Centar	Wind Speed	1.001	0.978	0.324
Rectorate	Temperature	4.132	20.108	0
Rectorate	Precipitation	2.431	3.423	0.021
Rectorate	Relative Humidity	1.001	5.474	0.021
Rectorate	Wind Speed	3.54	1.722	0.136
Karposh	Temperature	4.29	15.426	0
Karposh	Precipitation	2.104	5.38	0.003
Karposh	Relative Humidity	2.222	4.329	0.006
Karposh	Wind Speed	1.001	2.364	0.126
Lisiche	Temperature	4.297	13.623	0
Lisiche	Precipitation	3.031	4.79	0.002
Lisiche	Relative Humidity	2.014	7.58	0
Lisiche	Wind Speed	1.001	0.004	0.957
Gazi Baba	Temperature	4.299	10.661	0
Gazi Baba	Precipitation	3.993	4.521	0.001
Gazi Baba	Relative Humidity	1.763	8.234	0
Gazi Baba	Wind Speed	1.001	4.363	0.039
Kumanovo	Temperature	3.054	13.231	0
Kumanovo	Precipitation	1.001	9.761	0.002
Kumanovo	Relative Humidity	2.961	1.31	0.34

Kumanovo	Wind Speed	2.351	0.93	0.465
Bitola 1	Temperature	2.85	8.971	0
Bitola 1	Precipitation	1.001	2.922	0.09
Bitola 1	Relative Humidity	1.298	0.236	0.832
Bitola 1	Wind Speed	2.392	7.686	0
Bitola 2	Temperature	5.363	27.756	0
Bitola 2	Precipitation	1	3.277	0.072
Bitola 2	Relative Humidity	1.001	1.189	0.278
Bitola 2	Wind Speed	1	1.351	0.247

Source: Compiled by author, 2025

The combined smoothed term analysis across the eight gauges (Centar, Rectorate, Karposh, Lisiche, Gazi Baba, Kumanovo, Bitola 1, and Bitola 2) consistently identifies temperature as the most influential factor, with statistically significant effects ($p < 0.001$) in every location and high F-values, peaking at 27.756 in Bitola 2, indicating a strong nonlinear relationship (Figure 2). In contrast, relative humidity and wind speed often show weaker or inconsistent significance. Relative humidity is completely non-significant in Bitola 1 and Bitola 2 ($p = 0.832$ and 0.278), while wind speed has a minimal effect in Centar and Karposh ($p = 0.324$ and 0.126 respectively). Interestingly, wind speed is a significant factor only in Bitola 1 ($p = 0.000$) and Gazi Baba ($p = 0.039$), which indicates local environmental or topographical influence. Again, the strongest F-value is for temperature in Bitola 2, while the weakest model effect is for wind speed in Lisiche (F-value of only 0.004). Air temperature also had the highest estimated degrees of freedom (edf) in terms of model complexity especially in Bitola 2 (edf = 5.363) indicating a complex, non-linear contribution to the response variable. Temperature was identified as the most influential climate variable across all monitoring sites, whereas precipitation, relative humidity, and wind speed exhibited spatially variable effects. At several gauges, these variables showed little or no influence on PM_{10} concentrations, highlighting the spatial heterogeneity of pollutant and climate interactions.

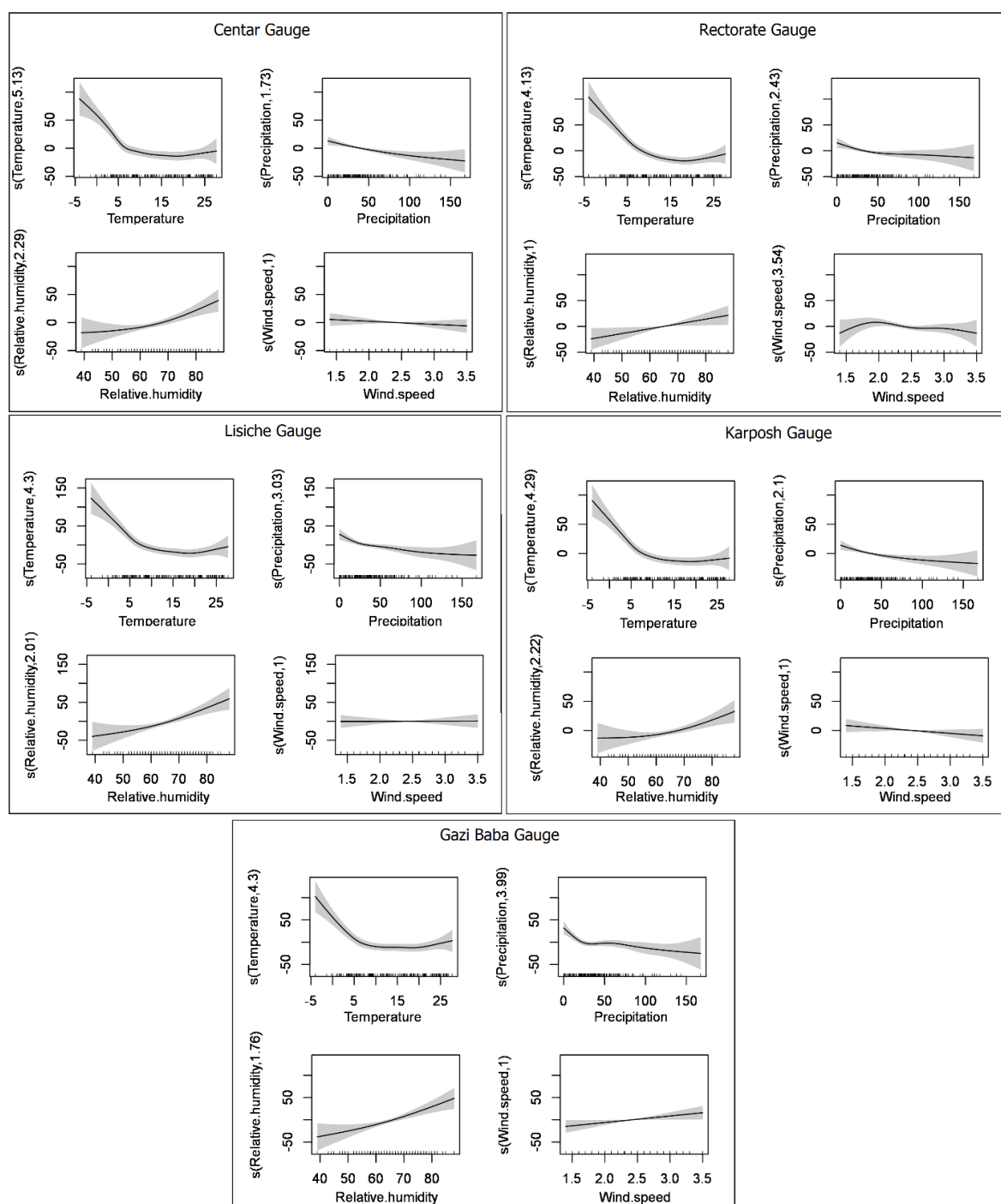


Figure 2. GAM component plots for Skopje gauges. Source: authors

Figure 2 shows the component plots from the gauges in Skopje, using a Generalized Additive Model (GAM) illustrating the non-linear effects of temperature, precipitation, relative humidity and wind speed on PM_{10} . The spline plots for the Centar gauge show that air temperature has a strong non-linear effect on PM_{10} , with the response decreasing sharply from low to moderate temperatures before flattening at higher values. Precipitation exhibits a slight, predominantly linear negative effect, while relative humidity has a clear positive influence, particularly above 65%. In contrast, wind speed seems to have little or no apparent effect on the PM_{10} concentrations. Overall, temperature and humidity are the most important predictors for Centar gauge.

The GAM analysis for PM_{10} at the Rectorate station shows that PM_{10} levels decrease sharply with increasing temperature, especially between $-5^{\circ}C$ and $10^{\circ}C$, and slightly rise

again at higher temperatures. Precipitation has a small negative impact on PM_{10} , which suggests that rainfall contributes to the reduction of particle concentration. In the case of relative humidity, a steady positive correlation was observed, indicating that the increased humidity could be aiding the accumulation of PM_{10} . The effect of wind speed is nonlinear with the lowest PM_{10} around 2.5 m/s; both lower and higher wind speeds are associated with increased levels of PM_{10} , which can be a consequence of stagnation or particle resuspension. The patterns show the complexity of the environmental influences on the PM_{10} dynamics.

At the Lisiche station, PM_{10} levels decrease significantly with increasing temperature, especially from -5°C to approximately 10°C , then plateau and slightly increase above 20°C . Precipitation demonstrates a decreasing trend on PM_{10} , especially at the lower levels, suggesting its capacity for particle scavenging. Relative humidity has a positive influence on the formation of particulate matter, where high humidity is associated with higher PM_{10} concentrations. Wind speed, however, has no significant pattern, which indicates little influence on PM_{10} in this area. Overall, temperature, humidity, and precipitation are the dominant factors affecting PM_{10} levels in Lisiche.

Similar results are obtained for the temperature with the gauge Lisiche, where the concentrations of PM_{10} decrease abruptly with increasing temperature, especially between -5°C and 10°C and stay low at higher temperature with a slight increase above 20°C . PM_{10} shows a decreasing trend with precipitation, especially at lower amounts, supporting its role in pollutant washout. Relative humidity showed a positive correlation with PM_{10} , with a more pronounced increase when above 70 %. Wind speed has a weak negative effect, meaning that stronger winds may slightly decrease PM_{10} levels. In general, temperature, humidity and precipitation are the main factors that influence PM_{10} in Karposh, whereas wind speed has a minor influence.

PM_{10} levels at Gazi Baba decrease sharply with increasing temperature, indicating high temperature sensitivity and possibly reflecting the influence of local heating sources or inversion conditions during colder periods. Precipitation has a significant negative effect, especially up to 50 mm, suggesting efficient removal of particles. PM_{10} shows a gradual but steady increase with relative humidity, particularly above 65%. Wind speed shows a slight positive trend, which is unique among the gauges and may be due to local resuspension of dust or other particulate sources activated by airflow. It can be concluded that temperature and precipitation are the most important predictors, with humidity and wind having a moderate effect at this gauge.

The next Figure 3 presents the GAM component plots for Kumanovo gauge for temperature, precipitation, relative humidity and wind speed.

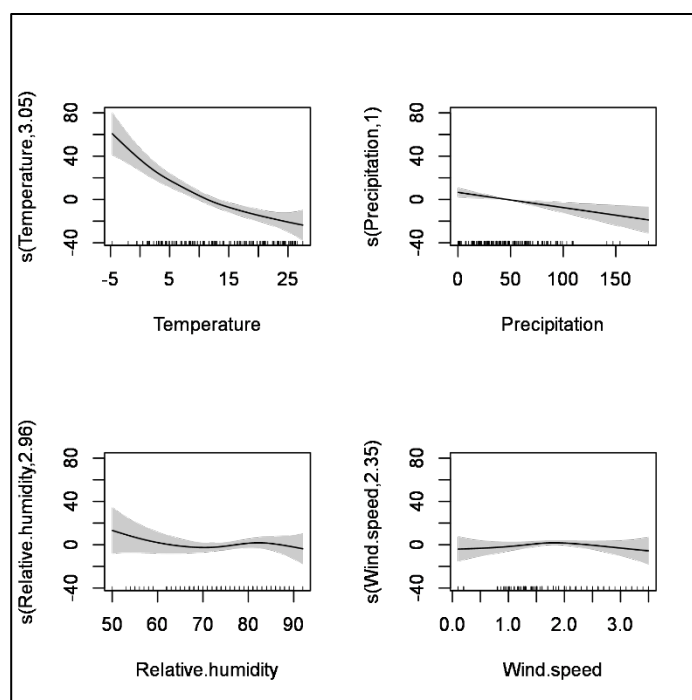


Figure 3. GAM component plots for Kumanovo gauge

At the Kumanovo station, PM_{10} concentrations gradually decrease with increase of temperature, showing a smooth and almost linear decline for roughly between $-5^{\circ}C$ and $25^{\circ}C$. Precipitation is also negatively associated with PM_{10} , indicating that higher levels of rainfall are linked to lower concentrations of particles as a consequence of the washing out of airborne pollutants. Relative humidity, in contrast, shows a slight, mostly flat pattern, suggesting it has little effect on PM_{10} levels. The effect of wind speed is also weak, with only a slight increase in PM_{10} around 1.5 m/s, indicating a limited role in pollutant dispersion. In general, the main factors influencing PM_{10} concentrations in Kumanovo are temperature and precipitation, while relative humidity and wind speed have much less pronounced effects.

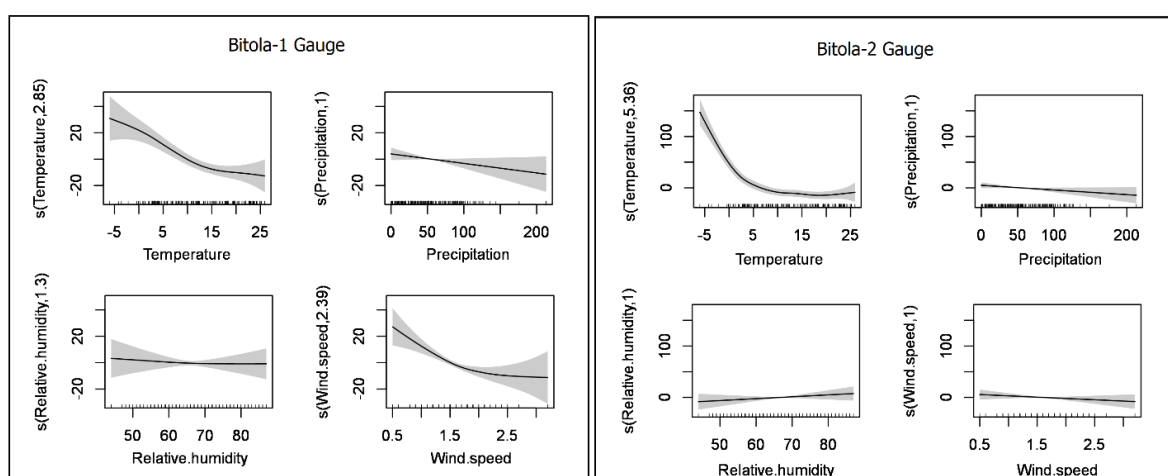


Figure 4. GAM component plots for Bitola gauges.

In Bitola 1, the concentrations of PM_{10} tend to decrease gradually with the increase of temperature, with a less pronounced and smooth decline than in most of the other monitoring stations, indicating a moderate temperature effect. Precipitation is weakly negatively correlated with PM_{10} , meaning that higher precipitation tends to correspond to lower particle concentrations. The relative humidity presents a nearly flat response over

the observed range, with a negligible effect on the PM₁₀ concentrations. Wind speed, however, shows a clearer trend, with PM₁₀ concentrations decreasing with increasing wind speed, especially from 0.5 to 2.0 m/s, suggesting the importance of wind-driven dispersion at this site. Overall, temperature and wind speed appear to be the main factors influencing PM₁₀ concentrations at Bitola 1, while precipitation has a weaker effect and relative humidity has little influence.

At Bitola 2, PM₁₀ concentrations decrease sharply with increasing temperature, showing a more pronounced nonlinear response than at most other monitoring stations. Precipitation shows a weak but consistent negative relationship with PM₁₀, suggesting that higher rainfall is generally associated with lower particle concentrations through wet deposition. Relative humidity and wind speed show only slight trends, indicating that both variables have little influence on PM₁₀ concentrations at this site. Temperature is the dominant factor influencing PM₁₀ variability at Bitola 2, whereas the effects of the other climate variables are comparatively weak.

The results shown on (Table 5) has the results shown summarized and compared to each gauge.

Table 5. Results

Location	Temperature	Precipitation	Relative Humidity	Wind Speed
Centar	– Significant (p = 0.000)	– Significant (p = 0.001)	+ Significant (p = 0.001)	– Not sig. (p = 0.324)
Rectorate	– Significant (p = 0.000)	– Significant (p = 0.021)	+ Significant (p = 0.021)	– Not sig. (p = 0.136)
Karposh	– Significant (p = 0.000)	– Significant (p = 0.003)	+ Significant (p = 0.006)	– Not sig. (p = 0.126)
Lisiche	– Significant (p = 0.000)	– Significant (p = 0.002)	+ Significant (p = 0.000)	– Not sig. (p = 0.957)
Gazi Baba	– Significant (p = 0.000)	– Significant (p = 0.001)	+ Significant (p = 0.000)	– Significant (p = 0.039)
Kumanovo	– Significant (p = 0.000)	– Significant (p = 0.002)	– Not sig. (p = 0.340)	– Not sig. (p = 0.465)
Bitola 1	– Significant (p = 0.000)	– Not sig. (p = 0.090)	– Not sig. (p = 0.832)	– Significant (p = 0.000)
Bitola 2	– Significant (p = 0.000)	– Not sig. (p = 0.072)	– Not sig. (p = 0.278)	– Not sig. (p = 0.247)

Source: Compiled by author, 2025.

Comparing the gauges, air temperature consistently shows a significant negative correlation with PM₁₀ concentrations, with p-values < 0.001 at every monitoring station. This indicates that as temperatures increase, PM₁₀ levels tend to decrease which is likely due to residential heating and enhanced atmospheric dispersion under warmer conditions (Manevska et al., 2025). Precipitation also shows a generally negative and significant effect on PM₁₀ in several gauges, notably Centar, Rectorate, Karposh, Lisiche, Gazi Baba, and Kumanovo, suggesting that rainfall helps remove particles from the air through wet scavenging. However, this effect is not statistically significant in Bitola 1, Bitola 2, which may be due to local differences in rainfall patterns, pollutant sources or topography. Regarding the relative humidity, a significant positive relationship is observed in urban stations such as Centar, Rectorate, Karposh, Lisiche, and Gazi Baba, indicating that higher humidity is associated with increased PM₁₀ possibly due to moisture helping particles stay airborne or grow in size. In contrast, Kumanovo and both Bitola gauges show no significant humidity effect, implying weaker or more complex interactions between moisture and particle behavior. Wind speed has a statistically significant negative effect in Gazi Baba and Bitola 1 station, highlighting its role in dispersing

pollutants in these areas. In other stations, wind speed is not significantly related to PM_{10} levels, suggesting it may not be a dominant climate factor in PM_{10} variation at those locations.

After conducting the model, we tested the results using the residual analysis (Table 6). The main criteria for analyzing were R^2 , RMSE, AIC and ANOVA.

Table 6. Residual analysis

Gaug	Centa	Rectorat	Karpos	Lisich	Gazi	Kumano	Bitola	Bitola
R^2	0.741	0.734	0.725	0.737	0.653	0.637	0.507	0.713
RMSE	15.834	16.694	15.438	23.289	18.355	11.581	10.080	14.554
AIC	791.95	807.086	784.72	902.30	834.21	702.499	662.81	767.84
ANOV	<	< 0.0001	<	<	<	< 0.0001	<	<

Source: Compiled by author, 2025

R^2 tells us how well the model explains the variability in PM_{10} levels.

The best model fits are at Centar (0.741), Lisiche (0.737), and Rectorate (0.734). These models explain over 73% of the variation in PM_{10} concentrations. Bitola 1 has the lowest R^2 (0.507), meaning it explains only around 51% of the variation, making it the weakest model in terms of explanatory power.

RMSE shows how far off the model's predictions are from the actual values where lower values meaning more accurate predictions.

Bitola 1 (10.080) and Kumanovo (11.581) have the lowest RMSE, this indicates that their models make more precise predictions, even though their R^2 is lower. Lisiche (23.289) has the highest RMSE, showing that its model predictions deviate the most from observed values.

AIC evaluates the model's performance while penalizing complexity, lower values mean better models. Bitola 1 (662.812) and Kumanovo (702.499) have the lowest AIC, suggesting their models are the most efficient in balancing fit and simplicity. Lisiche (902.309) has the highest AIC, meaning the model might be overcomplicated or not well-fitting.

According to the ANOVA (p values) all gauges showed p-values < 0.0001, meaning they are statistically significant which explains that the variables (air temperature, precipitation, humidity and wind speed) are meaningfully related to PM_{10} levels at all stations.

5. Discussion

The main purpose of this study was to investigate the influence of climate parameters on PM_{10} concentrations in different urban areas of North Macedonia by applying Generalized additive models (GAMs). The results confirm that climate variables explain a large proportion of the variability in PM_{10} at all the monitoring stations, although their influence varies spatially. Air temperature was the most important predictor at all stations, whereas precipitation and wind speed showed local cleansing effects. Relative humidity was the only climate variable that showed positive correlation with particulate matter. The results support the hypothesis that climate conditions play a major role in PM_{10} variability but their effects are modulated by local emission sources and urban characteristics.

The effect of climate conditions on PM_{10} concentrations has been confirmed in many studies using linear and non-linear models (Mentzakis and Delfino, 2010; Belušić et al., 2015; Munir et al., 2015; Ferenczi et al., 2021; Adamek and Ziernicka-Wojtaszek, 2019). Generalized Additive Models are widely used to model nonlinear relationships. The results for the three largest urban areas in North Macedonia were compared to earlier GAM studies from Oslo (Aldrin and Haff, 2005) and Zagreb (Belušić et al., 2015).

Our results confirm that PM_{10} concentrations are strongly influenced by climate conditions similar to Oslo. Unlike the results obtained in Zagreb, where the PM_{10} concentrations increased with temperature due to photochemical activity and SO_2 oxidation, this study found a strong association between lower temperatures and higher PM_{10} concentrations, especially when the temperature was below 0 °C. The association probably reflects increased residential heating in winter and decreased atmospheric mixing, so temperature represents both climate processes and seasonal anthropogenic emissions.

The effect of precipitation, wind speed and relative humidity varied between monitoring stations, displaying distinct spatial variation. The results have shown that precipitation has a cleansing effect at most of the stations, in agreement with the previous results obtained in Zagreb. An exception was Bitola 1 where higher PM_{10} concentrations were sometimes found to coincide with heavier precipitation, possibly due to short-term resuspension of deposited particles or temporary vertical mixing prior to the dominance of wet deposition. Wind speed was also spatially variable. In general, low wind speeds were associated with higher PM_{10} concentrations due to poor atmospheric dispersion, but only Bitola 1 showed a statistically significant decrease of PM_{10} with increasing wind speed. The fact that Bitola 1 and Bitola 2 are very close to each other, but their responses are different, shows that local factors such as density of buildings, configuration of the terrain and distance from the emission sources can have a great impact on the dispersion of pollutants. Also, relative humidity was found to have a nonlinear relation with PM_{10} with concentrations increasing up to about 80% humidity and then decreasing due to wet scavenging processes. This pattern was especially evident at the Lisiche and Gazi Baba stations, and is in line with observations reported from Zagreb.

In order to compare the testing of the model, in Table 7 we compared one gauge from each city for the R^2 values of the mentioned researches.

Table 1. R^2 values

Gauge	Centar	Kumanovo	Bitola	Loren	Zagreb
R^2	0.74	0.64	0.71	0.72	0.43

Source: Compiled by author, 2025

The comparison shows that the model gave the best explanatory power in Centar ($R^2 = 0.74$) followed by Loren in Oslo ($R^2 = 0.72$), Bitola ($R^2 = 0.71$), Kumanovo ($R^2 = 0.64$) and Zagreb ($R^2 = 0.43$). This shows that climate conditions explain a larger share of the PM_{10} variability in the Macedonian cities than in Zagreb. The lower explanatory power in Kumanovo indicates that other local influences such as traffic, industrial activities, residential heating intensity or land-use characteristics may be more important for PM_{10} concentrations. Differences between the monitoring stations suggest that local urban structure and emission sources modify the relationship between climate conditions and particulate pollution.

The results also have important implications for air quality management. Low temperatures are consistently associated with high PM_{10} concentrations, so mitigation measures should be primarily targeted at the winter heating season through the promotion of cleaner household heating technologies, phasing out inefficient wood-burning stoves and expanding district heating systems. Furthermore, meteorological forecasts could be integrated into early-warning systems to provide pollution alerts under conditions of low temperature, low wind and stable atmospheric conditions. The observed station-specific differences also suggest that air-quality management should be adapted to local conditions, with a stronger focus on residential heating in residential neighbourhoods, traffic management in densely urbanised areas and urban planning measures to improve natural ventilation.

To summarize, the study shows that climate conditions are an important driver of PM_{10} concentrations in North Macedonia, but their effects are strongly modulated by local

urban characteristics and anthropogenic emission sources. Future studies should integrate climate variables with information on traffic, residential heating, industrial emissions, land use and urban morphology to achieve a more complete understanding of spatial differences in PM_{10} concentrations and to underpin more effective urban air-quality policies.

6. Conclusions

This study indicates that the concentrations of PM_{10} in different urban areas in North Macedonia are significantly affected by climatic factors, with considerable spatial variability. Temperature was the most consistently significant predictor at all stations, with PM_{10} levels generally increasing as temperatures decreased which is a pattern particularly evident in winter months, likely driven by increased fuel combustion. This differs from the findings in Zagreb, where higher temperatures were associated with increased PM_{10} , suggesting the importance of regional heating practices and emission sources.

Relative humidity has a nonlinear effect on PM_{10} , especially in Lisiche and Gazi Baba. PM_{10} concentrations generally increased with relative humidity up to around 80%, then declined at higher humidities, indicating a threshold where aerosol formation gives way to wet scavenging mechanisms like fog or rain. This dual behavior is consistent with observations from Zagreb and supports the relevance of humidity in modulating pollution, especially in different atmospheric moisture conditions.

Precipitation generally showed a cleansing effect by reducing PM_{10} levels through wet deposition. However, in some stations as Bitola 1, the moderate rainfall did not decrease PM_{10} as expected, possibly due to resuspension of particles or temporary mixing effects. Wind speed also presented site-specific patterns. Although stronger winds generally contributed to PM_{10} dilution through dispersion, significant effects were only observed at selected stations (Bitola 1 and Gazi Baba) suggesting the influence of local topography and potential pollutant transport from upwind industrial areas.

The results of model testing indicate that the GAMs performed well at most gauges. The R^2 values ranging from 0.507 (Bitola 1) to 0.741 (Centar) show moderate to strong explanatory power, with most gauges above 0.7, suggesting that climate conditions have a significant impact on PM_{10} concentrations, especially in urban areas such as Centar, Rectorate and Lisiche.

The RMSE values further confirm the accuracy of the predictions, with lower errors in Kumanovo and Bitola 1 indicating more consistent pollution behavior or simpler atmospheric conditions. Meanwhile, higher RMSE at Lisiche indicates more complex or variable local influences. AIC values show a similar trend in that lower scores (e.g., Bitola 1 and Kumanovo) indicate more parsimonious models, whereas higher scores (e.g., Lisiche and Gazi Baba) may indicate model complexity or noise in the data.

The statistical significance of all models was high (ANOVA $p < 0.0001$), supporting the robustness of the results. Overall the testing shows that while the models have performed well, the differences in fit, error and complexity highlight the need for taking into account local emissions, topography and other contextual factors when modeling air quality dynamics.

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Appendix:

Author contributions: All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Emilija Manevska, Olgica Dimitrovska and Ivan Radevski. Svemir Gorin, Arse Kuzmanoski and Ana M. Petrović contributed in data collection, cartography, review and editing. The first draft of the manuscript was written by Emilija

Manevska, all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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