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# The relationship of atmospheric pollutants and meteorological variables for the Sofia region, Bulgaria

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**Abstract.** The research on the relationship between meteorological conditions and atmospheric air pollution in Sofia city was conducted based on 1-hour data on meteorological variables (air temperature, global solar radiation, wind speed) and atmospheric pollutants (NO<sub>2</sub>, CO, O<sub>3</sub>, SO<sub>2</sub>, PM<sub>10</sub>) for 2012-2016. As a result of the correlation and regression analysis of the influence of meteorological variables on the daily concentrations of atmospheric pollutants, the strongest effect is expressed in ozone (O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>) and particulate matter (PM<sub>10</sub>). In urban areas, air temperature (AT), the intensity of global solar radiation (GSR) and, wind speed (WS) have a stronger impact on the concentration of pollutants. There is a strong correlation between air temperature (r =  $0.53 \div 0.76$ ) and solar radiation (r =  $0.65 \div 0.77$ ) with ozone concentrations. An exception is the area of Orlov most, where there is an average correlation with temperature and a minor correlation with solar radiation. In regions (except Kopitoto) there are average correlations between air temperature and PM<sub>10</sub>, SO<sub>2</sub>, and CO (r =  $0.55 \div 0.62$ ). There is a weak correlation between NO<sub>2</sub> and air temperature and solar radiation in the areas of Druzhba and Nadezhda.

**Key words:** air pollution, meteorological variables, nitrogen dioxide, ozone, sulfur dioxide, particulate matter.

#### Introduction

Weather conditions have a significant impact on the processes of diffusion of emissions of harmful substances from various sources, as well as on the level of ground-level pollution and air quality in urban and suburban environments. Between atmospheric pollution and a number of meteorological variables such as air temperature, humidity, precipitation, wind direction and wind speed, global solar radiation has a certain relationship described by a number of authors (Lazareva & Popova, 2014; Kryukova & Simakina, 2015; Kadinov, 2019a,b; Kerimray et al., 2020; Bozhkova, 2020, Kadinov, 2021a,b). According to other authors (Seinfeld & Pandis, 1998; Altwicker et al., 1999; Collier, 2006; Bagitova & Nyssanbayeva, 2018), meteorological phenomena and changes in weather conditions are related to the chemical state and processes in the atmosphere, and hence to air quality. For the study of the influence of meteorological variables on atmospheric pollutants, the methods of mathematical statistics are mainly applied – correlation and regression (linear and multiple) analyses (Song et

al., 2020; Hu et al., 2021; Pasic et al., 2023; Khedekar & Thakare, 2023). Based on these dependencies., Gong et al. (2015) and Radaideh (2017) found that wind speed has a direct impact on urban air pollution. Increasing speed affects the dispersion of pollutants and reduces their concentration, while low speed is associated with local pollution. Wind speed directly affects the levels of PM, sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>) and carbon monoxide (CO) (Gorai et al., 2015; Kadinov, 2019a,b; Taleghani, 2022) and the variable tropospheric ozone (Jammalamadaka & Lund, 2006; Kadinov, 2021a) as the concentration of its precursors decreases with increasing speed. Strong winds can also have the opposite effect long-distance transport of dust and PM (Mues, 2013; Chen et. al., 2015; Yin et al., 2016). The role of wind direction on air pollution is mainly related to the specific conditions in the area (Tian et al., 2014; Xie et al., 2022). Wind direction and speed, as well as atmospheric pressure, play an important role in the occurrence of episodes with high concentrations of PM<sub>10</sub> (Kadinov, 2021b). The authors who have studied the thermal regime of the atmosphere believe that it significantly affects the retention and distribution of pollutants (Doncheva-Boneva et al., 2017; Soyol-Erdene et al., 2021; Morozov & Starodubceva, 2020). Temperature inversions and fogs in the cold period of the year are unfavorable for the dispersion of pollutants (Morozov & Starodubceva, 2020; Rendon et al., 2014). A strong negative correlation of air temperature was found with CO and NO<sub>x</sub> (Hester & Harrison, 2009; Wu et al., 2013; Ruan et al., 2021). Higher concentrations of global dust and SO<sub>2</sub> are associated with lower temperatures directly as a result of their retention in the ground layer (Rogalski et al., 2014) and indirectly due to an increase in their emissions in the winter (Zyromski et al., 2014; Bernhard et al., 2023).

PM and ozone (O<sub>3</sub>) are especially sensitive to temperature, a strong positive correlation with ozone (Gvozdić & Kovač-Andrić, 2011; Bernhard et al., 2023) and much weaker with PM (Chen et al., 2021) has been proven, a negative correlation with nitrates in the air (Ge et al., 2017) and an ambiguous correlation with the precursors of PM (Li et al., 2015; Prakash et al., 2022). In addition to temperature, the high intensity of solar radiation activates photochemical reactions in the atmosphere, leading to the formation of ozone and

other photooxidants. Peteva & Luybenova (2019) note the influence of anthropogenic factors on PM<sub>10</sub>. Arslan (2023) found a significant positive correlation between global solar radiation and tropospheric ozone concentrations and a negative correlation with NO<sub>x</sub> levels in atmospheric air. Sulfur dioxide levels do not show an unambiguous dependence on global solar radiation (Morozov & Starodubceva, 2020). Kadinov (2019a) found a negative correlation between PM<sub>10</sub> concentration and basic meteorological variables such as air temperature, solar radiation, and wind speed. The relationship between weather conditions and air pollution is the subject of much scientific research. The impact of various meteorological variables on air quality is interrelated, and it is difficult to distinguish one from the other.

The intervention of many other factors such as terrain, location, urbanization, architecture, infrastructure, etc., as well as the established relationships between weather variables and atmospheric pollutants do not always give a clear answer.

The aim of the present study is to search for relationships between some meteorological variables (air temperature (AT), global solar radiation (GSR), wind speed (WS)) and atmospheric pollutants levels (NO<sub>2</sub>, CO, O<sub>3</sub>, SO<sub>2</sub>, PM<sub>10</sub>) for the Sofia region by applying correlation and regression analysis.

# Materials and Methods Study area

The city of Sofia (the capital of Bulgaria) is located in the central part of the Sofia Valley at an altitude of 520-560 m above sea level on a territory of 492 km<sup>2</sup>. The Sofia valley extends from northwest to southeast between the Stara Planina in the north and the Viskyar, Lyulin, Vitosha and Lozenska mountains in the south. The city of Sofia is highly urbanized, with heavy vehicular traffic, high residential density and industrial activity.

The territory of Sofia falls in the climatic region of the high fields of Western Central Bulgaria to the temperate-continental climate subregion of the European-continental climate area (Stanev et al., 1991). The type of the underlying surface, the relief and altitude, the exposure of the slopes and the direction of the extension of the walled mountains transform the influence of solar radiation and atmospheric circulation. For the Sofia valley, radiation inversions are a typical phenomenon. The longest ground inversions are recorded during the cold half of the year - autumn and winter, which is associated not only with low temperatures, but also with the large number of cases of calm weather. Inversions are the most unfavorable conditions for the spread of pollutants in the ground layer. In global, about 230 days with nocturnal inversions can be observed throughout the year, the maximum is observed in August and September, and the minimum is in February.

Six study areas (Druzhba, Hypodrum, Pavlovo, Nadezhda disricts, Orlov most station and the Kopitoto area, Vitosha Nature Park) were selected as they represent areas where automatic measuring stations of the atmospheric air monitoring network are located, where simultaneously with atmospheric pollutants such as PM<sub>10</sub>, sulfur dioxide, nitrogen dioxide, ozone and carbon monoxide, the main weather variables are measured - air temperature (AT), relative humidity (RH), global solar radiation (GSR), wind speed (WS) and direction (Fig.1).

The automatic measurement stations are divided into:

\* Urban background – influenced by emissions from transport, household sources, industrial sources: Druzhba (1), Pavlovo (3), Nadezhda (4).

\* Urban background – influenced by emissions from transport and household sources: Hypodrum (5).

\* Transport – under the influence of emissions of motor transport: Orlov most (2).

\* Country background – influenced by the transfer of pollutants: Kopitoto (6).



Fig. 1. Location of automatic measurement stations: 1- Druzhba, 2 - Orlov most, 3 - Nadezhda, 4 - Pavlovo, 5 - Hypodrum, 6 - Kopitoto (Kadinov, 2019b).

Stefanov et al. (2011) found that the main contribution to the formation of the average annual and 24-hour concentrations of PM and nitrogen dioxide, not only in the Orlov most station, but also in the neighborhoods, is the transport - over 80%. Kadinov (2019b) found that fine dust particles and nitrogen oxides have a significant impact on air quality in the city of Sofia.

For the purposes of the present study, a database of validated data for 1-hour concen-

trations of atmospheric pollutants and meteorological variables, provided by the Executive Environment Agency through a request for access to information from 2012, was used.

#### Methodical approach

To determine the presence of statistical relationships between atmospheric pollutant concentrations and meteorological variables, regression analysis was used. A special place in regression analysis is occupied by linear regression analysis, or the linear regression model of the relationship between two random variables x and y. The equation of the linear regression model has the form:

$$y_x = ax + b,$$

where x is variable, a and b are regression coefficients.

The equations of linear regression between two variables x and y can also be presented in the following form:

$$y - y_0 = R_{y/x}(x - x_0)$$
  
 $x - x_0 = R_{x/y}(y - y_0)$ 

where:

 $x_0$  and  $y_0$  - arithmetic mean of the x and y series;  $R_{y/x}$  and  $R_{x/y}$  - regression coefficients.

Regression coefficients ( $R_{y/x}$  and  $R_{x/y}$ ) are determined by the formulas:

$$R_{y/x} = r \frac{\sigma_y}{\sigma_x}$$
$$R_{x/y} = r \frac{\sigma_x}{\sigma_y}$$

where:

*r* – correlation coefficient between rows *x* and *y*;  $\sigma$  –standard deviation.

The correlation coefficient (*r*) is calculated by the formula:

$$r = \frac{\sum_{1}^{n} (x_{i} - x_{0}) (y_{i} - y_{0})}{\sqrt{\sum_{1}^{n} (x_{i} - x_{0})^{2} \sum_{1}^{n} (y_{i} - y_{0})^{2}}}$$

The root mean square deviations ( $\sigma_x$  and  $\sigma_y$ ) for the *x* and *y* series are determined by the following formula:

$$\sigma_x = \sqrt{\frac{(x_i - x_0)^2}{n - 1}}$$
$$\sigma_y = \sqrt{\frac{(y_i - y_0)^2}{n - 1}}$$

The correlation coefficient (r) is a criterion that expresses the degree of linear relationship between the two variables, its value can take meanings from -1.0 to +1.0. In the case of r=0 the relationship between two phenomena does not exist, and in the case of  $r=\pm1$ , the relationship is functional. In other cases, i.e. in the case of -1 < r<+1, the relationship is correlative. Its negative value indicates the existing feedback between the signs, while the positive meaning indicates a straight line. The greater its value in absolute value up to 1, the stronger the correlation between x and y. We distinguish the following degrees of correlation:

- |r| > 0.7 strong correlation
- $0.5 < |r| \le 0.7$  average correlation
- $0.3 < |r| \le 0.5$  weak correlation
- |r| < 0.3 minor correlation

With positive values of the coefficient r, there are straight-line dependencies, in which as the variable y increases, the variable x also increases, and with a negative value of r, with an increase in x, the values of y decrease. With negative values of the correlation coefficient, the regression coefficient is also negative and vice versa.

#### **Results and Discussion**

The assessment of the impact of meteorological variables on some atmospheric pollutants in the area of the city of Sofia was carried out using correlation and regression analysis.

The correlation coefficients of the relationship between the average daily values of atmospheric pollutant concentrations and meteorological variables over a five-year period by station are presented in Table 1.

From the presented data, it can be seen that in most of the areas considered, there is a strong correlation between air temperature and solar radiation with ozone concentrations. The same strong correlation was found by other authors (Gvozdić & Kovač-Andrić, 2011; Bernhard et al., 2023). An exception is the station of Orlov most, where there is an average correlation with temperature and an insignificant – with solar radiation. With the exception of the Kopitoto area, in the other areas there are average correlations between air temperature and concentrations of  $PM_{10}$ , SO<sub>2</sub>, CO. Such a corelation for  $PM_{10}$  was found by Chen at al. (2021) while Kadinov (2019a) found out a negative correlation between  $PM_{10}$ , temperature, solar radiation, and wind speed. There is a weak correlation between the  $NO_2$  with air temperature and solar radiation in the areas of

Druzhba and Nadezhda. According to some authors (Hester & Harrison, 2009; Wu et al., 2013; Ruan et al., 2021) the corelation between air temperature CO and  $NO_x$  was strongly negative.

**Table 1.** Correlation coefficients between daily concentrations of the main pollutants and meteorological variables in the considered areas.

Variables	AT	GSR	Р	WS	Variable	AT	GSR	Р	WS
Druzhba				Hypodrum					
NO <sub>2</sub>	-0.557	-0.451	0.048	-0.141	NO <sub>2</sub>	-0.274	-0.276	-0.040	-0.384
O <sub>3</sub>	0.719	0.776	0.041	0.048	O <sub>3</sub>	0.528	0.650	0.107	0.235
SO <sub>2</sub>	-0.402	-0.275	0.191	0.125	SO2	-0.517	-0.400	-0.138	0.186
$PM_{10}$	-0.346	-0.263	0.126	-0.248	PM10	-0.357	-0.310	-0.001	-0.235
CO	-	-	-		CO	-0.442	-0.419	-0.036	-0.175
	Р	avlovo				Ν	Jadezhda		
NO <sub>2</sub>	-0.292	-0.208	0.206	-0.502	NO <sub>2</sub>	-0.409	-0.311	-	-0.467
O3	0.659	0.716	-0.235	0.386	O <sub>3</sub>	0.570	0.683	-	0.309
SO <sub>2</sub>	-0.581	-0.351	0.177	-0.100	SO <sub>2</sub>	-0.348	-0.186	-	-0.043
PM <sub>10</sub>	-0.372	-0.261	0.265	-0.402	PM <sub>10</sub>	-0.356	-0.214	-	-0.337
CO	-0.526	-0.377	0.175	-0.347	CO	-0.409	-0.311	-	-0.467
Orlov most					]	Kopitoto			
NO <sub>2</sub>	0.079	-0.006		-0.275	NO <sub>2</sub>	-0.038	0.020	0.033	0.011
O <sub>3</sub>	-0.419	-0.276	-	0.158	O <sub>3</sub>	0.583	0.751	0.127	-0.279
SO <sub>2</sub>	-0.347	-0.286	-	-0.322	SO <sub>2</sub>	-0.110	-0.107	0.020	0.011
PM <sub>10</sub>	-0.492	-0.436	-	-0.274	PM <sub>10</sub>	0.467	0.418	0.213	-0.254
CO	-0.527	-0.439	-	-0.263	CO	-0.229	-0.327	0.104	0.149

Based on the obtained results of the correlation analysis, regression models of the relationships between ozone concentrations with air temperature and solar radiation were searched (Table 2). The models are linear or polynomial of the second order. The correlation coefficients of the regression models ranged  $r = 0.53 \div 0.76$ .

Regression models of the relationships between ozone concentrations and solar radiation have been obtained for certain areas of Sofia (Table 3). The models are linear with relatively high correlation coefficients  $r = 0.65 \div 0.77$ .

During the entire study period, the concentration of nitrogen dioxide in Druzhba and Nadezhda is influenced by air temperature ( $r = -0.44 \div -0.66$ ) and the intensity of solar radiation ( $r = -0.43 \div -0.55$ ). The air temperature affects in some years in Pavlovo (for 2013 year: r = -0.36 and for 2014 year: r = -0.40) and Orlov most (for 2015 year: r = 0.55). No significant correlations have been established for the Hypodrum. In Pavlovo ( $r = -0.44 \div -0.61$ ), Nadezhda ( $r = -0.32 \div -0.52$ ) and Orlov most ( $r = -0.29 \div -0.39$ ), an inverse correlation was

established between nitrogen dioxide and wind speed.

The concentration of sulfur dioxide in the areas of Pavlovo, Hypodrum, Nadezhda and Orlov most in the period 2012-2016 was influenced by air temperature, and the correlation coefficient for many years ranged from r = -0.33 to r = -0.68. In Druzhba, this influence was established only in 2012 and 2015. The influence of other meteorological elements is insignificant.

For carbon monoxide, there is a weak correlation with air temperature ( $r = -0.42 \div -0.57$ ) in the Hypodrum and Pavlovo quarters, and in the area of the Orlov most, and with the intensity of solar radiation ( $r = -0.37 \div -0.47$ ) in the Hypodrum and the Orlov most.

Regression models of the relationship between some of the harmful substances and the air temperature are presented in Table 4. The resulting models are polynomials of the first and second order. The relationships have an average correlation  $r = 0.55 \div 0.62$ .

Stations	Harmful substances	Regression model	R	
Air temperature (AT)				
Druzhba	O <sub>3</sub>	$y = 0.0632x^2 + 0.3123x + 22.523$	r = 0.76	
Hypodrum	O <sub>3</sub>	y = 1.2462x + 22.307	r = 0.53	
Pavlovo	O <sub>3</sub>	$y = 0.0885x^2 + 0.1174x + 26.983$	r = 0.73	
Nadezhda	O <sub>3</sub>	y = 1.5261x + 30.634	r = 0.59	
Kopitoto	O <sub>3</sub>	y = 1.7241x + 69.52	r = 0.62	

**Table 2.** Regression models of the relationship between the average daily ozone concentrations (y)and air temperature (x) in the considered stations.

**Table 3.** Regression models of the relationship between the average daily ozone concentration (*y*) and solar radiation (*x*) in the considered areas.

Stations	Harmful substances	Regression model	R	
Global solar radiation (GSR)				
Druzhba	O <sub>3</sub>	y = 0.148x + 14.436	r = 0.77	
Hypodrum	O <sub>3</sub>	y = 0.133x + 16.421	r = 0.65	
Pavlovo	O <sub>3</sub>	y = 0.2358x + 12.906	r = 0.73	
Nadezhda	O <sub>3</sub>	y = 0.2433x + 18.416	r = 0.69	
Kopitoto	O <sub>3</sub>	y = 0.1825x + 59.484	r = 0.76	

**Table 4.** Regression models of the relationship between the average daily concentrations of SO<sub>2</sub>, NO<sub>2</sub>, CO ( $\psi$ ) and air temperature (x) in the considered areas.

Stations	Harmful substances	Regression model	R		
Air temperature (AT)					
Hypodrum	SO <sub>2</sub>	$y = 0.0208x^2 - 0.8715x + 14.072$	r = 0.57		
Pavlovo	SO <sub>2</sub>	$y = 0.0264x^2 - 1.0799x + 15.341$	r = 0.62		
Druzhba	NO <sub>2</sub>	y = -0.9049x + 33.859	r = 0.62		
Orlov most	CO	y = -0.0404x + 1.564	r = 0.56		
Pavlovo	СО	$y = 0.0008x^2 - 0.0561x + 1.2975$	r = 0.55		

In addition to the established relationships between some of the pollutants and meteorological variables, the current work identifies regression relationships between the concentrations of individual harmful substances. Table 5 shows the regression models of the relationship between O<sub>3</sub> and its precursor NO<sub>2</sub> in some of the studied areas. The relationship is exponential or powerlaw with an average correlation ( $r = 0.65 \div 0.69$ ). Regression relationships between fine particulate matter and nitrogen dioxide have been found, with a strong correlation between these pollutants prevailing (Table 6)

Relatively close linear relationships were found between concentrations of fine solid particles and concentrations of carbon monoxide. There is a close exponential relationship between ozone and carbon monoxide (Table 7).

**Table 5.** Regression dependencies between the average daily ozone concentrations (y) and NO<sub>2</sub> (x) at the considered stations.

Stations	Harmful substances	Regression model	R		
NO <sub>2</sub>					
Druzhba	O <sub>3</sub>	$y = 609.96x^{-0.987}$	r = 0.66		
Hypodrum	O <sub>3</sub>	$y = 983.53x^{-1.053}$	r = 0.65		
Pavlovo	O <sub>3</sub>	$y = 85.273e^{-0.027x}$	r = 0.66		
Nadezhda	O <sub>3</sub>	$y = 84.93e^{-0.03x}$	r = 0.69		

Stations	Harmful substances	Regression model	R				
	NO <sub>2</sub>						
Druzhba NO <sub>2</sub> -PM <sub>10</sub>	$PM_{10}$	y = 1.8058x + 1.4855	r = 0.79				
Hypodrum NO <sub>2</sub> -PM <sub>10</sub>	$PM_{10}$	$y = 0.009x^2 + 0.945x + 0.0747$	r = 0.78				
Orlov most NO <sub>2</sub> -PM <sub>10</sub>	PM <sub>10</sub>	y = 1.4743x - 7.9524	r = 0.56				
Pavlovo NO <sub>2</sub> -PM <sub>10</sub>	PM <sub>10</sub>	$y = 0.0138x^2 + 0.4786x + 8.2956$	r = 0.87				
Nadezhda NO <sub>2</sub> -PM <sub>10</sub>	PM <sub>10</sub>	$y = 0.0232x^2 + 0.0011x + 19.279$	r = 0.84				
Pavlovo NO <sub>2</sub> -SO <sub>2</sub>	SO <sub>2</sub>	$y = 0.0012x^2 + 0.1011x + 3.7748$	r = 0.54				
Hypodrum NO <sub>2</sub> -CO	СО	$y = 0.0002x^2 + 0.0086x + 0.2139$	r = 0.77				
Pavlovo NO <sub>2</sub> -CO	СО	y = 0.0281x - 0.068	r = 0.82				

**Table 6.** Regression relationships between the average daily concentrations of fine particulate matter  $PM_{10}$ , SO<sub>2</sub>, CO (y) and NO<sub>2</sub> (x) at the considered stations.

**Table 7.** Regression dependencies between the average daily concentrations of ozone,  $PM_{10}(y)$  and CO (*x*) at the considered stations.

Stations	Harmful substances	Regression model	R		
СО					
Hypodrum CO-O <sub>3</sub>	O <sub>3</sub>	$y = 62.186e^{-0.94x}$	r = 0.75		
Hypodrum CO-PM <sub>10</sub>	$PM_{10}$	y = 59.659x - 4.688	r = 0.91		
Orlov most CO-PM <sub>10</sub>	PM <sub>10</sub>	y = 59.995x - 13.176	r = 0.93		
Pavlovo CO-PM <sub>10</sub>	$PM_{10}$	y = 58.357x - 5.5158	r = 0.90		
Pavlovo SO <sub>2</sub> -PM <sub>10</sub>	PM <sub>10</sub>	y = 3.019x + 17.29	r = 0.55		

# Conclusions

In conclusion, it can be emphasized that the main meteorological factors that affect the concentrations of atmospheric pollutants in Sofia are air temperature and solar radiation. The other weather variables, such as wind and atmospheric pressure, have a negligible effect. Close regression relationships between individual pollutants have been established. The regression models obtained can be used in restoring or extending the rows and in predicting the possible concentrations of atmospheric pollutants with the help of weather forecasts for the air temperature in Sofia.

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