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Investigation on the Dependence of Atmospheric Transparency on Concentration of Particulate Matter PM10

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Abstract
The present paper reports for an investigation on the dependence of atmospheric transparency on the concentration of particulate matter PM10. Models for calculation of the transparency from the PM10 concentration were developed for three monitoring sites in the municipality of Burgas: Automatic measuring station (AMS) Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar. An important problem for this region is the high levels of PM10 concentration which requires the development of new quantitative methods for studying and controlling air quality index (AQI) with respect for this important for our city atmospheric pollutant. The tests and checks carried out showed that the models developed are suitable for making quantitative assessments of the relationship between the transparency and the PM10 concentration in the atmospheric air.
Keywords: *transparency, зatmospheric pollution, method of multiple linear regression, coefficient of determination, F-statistics.*

1. Introduction

The high concentrations of air pollutants can have various unfavorable consequences on human health and the environment [1,2]. Air is everywhere around us and its pollution seriously affects the health of the population, especially that of the people living in urban areas.

The overall state of the atmospheric air is determined by the properties indicated in art,4 of the Clean Air Act [3]. The air quality index (AQI) for the municipality of Burgas [4] is calculated on the basis of seven of the controlled air pollutants: nitrogen dioxide, sulfur dioxide, PN10, hydrogen sulfide, ozone, styrene and benzene.

In the region of the municipality of Burgas, the main sources of the contamination with particulate matter are the diffuse emissions from the timber processing factory Kronospan, the load/unload of loose materials at the port of Burgas, the burning of solid fuel by communal-household sector during the cold seasons, the motor traffic and the pits for excavation of natural resources. Recently, an important problem of the municipality of Burgas became the comparatively high concentrations of particulate matter PM10 which required the development of new quantitative methods for studying and controlling air quality index (AQI) with respect for this important for our city atmospheric pollutant.

The main reason for the reduced transparency of the air is the absorption and scattering of light from solid and liquid particles present in the atmosphere. The deterioration of air transparency is due mainly to particles with sizes greater than that of molecules (for comparison, the typical size of a molecule is about 0,0002 μm) but smaller than 500 μm. The lifetime of a particle with such size before its precipitation can be from several seconds to several months. The precipitation rate of the particles sized from 0,1 to 1 μm is so small that they move throughout the atmosphere practically freely, depen-ding on the velocity and direction of the wind. The particles with sizes 20 μm or higher have substantially higher precipitation rate and can be removed by gravitational or inertia processes [2].

The present paper reports for an investigation on the dependence of atmospheric transparency on the concentration of particulate matter PM10.

2. Materials and Methods

The effect of light scattering in the atmosphere is connected with the presence of particles with sizes comparable to the wavelength of the visible light. The following formula for calculation of light scattering was suggested by *Mie*:

$$s = NK.\pi r^2, \qquad (1)$$

where: N is the number of particles per unit volume; r is particles radius; K factor of scattering efficiency (coefficient of scattering efficiency) depending on particles nature. For particle in the sub-micrometer range, $K = 6$ [5,6].

For single scattering, the law of *Bouquer-Lambert* can be used with certain approximations [7] to calculate the intensity of light at distance L from the source attenuated by atmospheric aerosols with extinction σ:

$$I = I_0.\exp(-\sigma L), \quad (2)$$

where: I_0 is the initial intensity of the light; I is the intensity of the light at distance L from the source; σ is the coefficient of attenuation of light (coefficient of extinction). The ratio I/I_0 cis called relative transmissivity. The product σL is called optical depth.

The relationship between the concentration of the particles in the atmosphere and visibility can be obtained if the human vision limit is known. [8]. It has been experimentally established that the lowest limit of vision for most people is reached when the light intensity decreases to 2% of the initial intensity of a non-fading beam. This allows substituting the relative transmissivity I/I_0 in eq.(2) with 0,02 and the distance L with the visibility L_V:

$$L_V = \frac{3{,}910230054}{\sigma}. \quad (3)$$

Formula (3) is the equation of Koschmieder where the coefficient of extinction is averaged across the wavelengths of the visible light although it is most often taken for the wavelength of 550 nm [6].

It is assumed that light attenuation is due only to scattering and the particles are spheres of equal sizes. Then, from eqs.(2) and (3) we obtain:

$$C = N.\frac{4}{3}\pi r^3.\rho \quad ;$$

$$L_V = \frac{5{,}21603067.\rho r}{KC}, \quad (4)$$

where: C is the concentration of the particles, μg/m^3.; ρ is the density of the particles, kg/m^3; r radius of the particles, μm.

The average density of the particle can be determined using the Clapeyron-Mendeleev equation for the state of the ideal gas: $pV = nRT$, where p – gas pressure, Pa; V – gas volume, m^3; R – universal gas constant (R = 8,314 J/mol.K); T – temperature, K; $n = m/M$ – amount of substance, mol; m – mass, kg; M – molecular mass of the air (M = 28,97.10^{-3} kg/mol):

$$\rho = \frac{pM}{RT}. \quad (5)$$

Substituting (5) in (4) and taking into account that $K = 6$ for sub-micrometer particles:

$$L_V = 3{,}02919507.\frac{p}{CT}. \quad (6)$$

For calculation of the visibility L_V, regression models of the following type were developed:

$$L_V = a\frac{1}{C} + b, \quad (7)$$

where: C is particles concentration, μg/m^3.

The coefficients a and b in eq.(7) are determined by regression analysis of experimental data [9,10].

The coefficient of dustiness was also determined as it is another quantitative measure of atmospheric opacity. The coefficient of dustiness as a number equal to the optical density divided by 0,01. The optical density is considered to be the base 10 logarithm of atmospheric opacity and opacity is a value reciprocal to the relative transmissivity I/I_0.

The formula for calculation of the coefficient of dustiness K_{dust} is:

$$K_{dust} = \frac{lg\left(\frac{I_0}{I}\right)}{0{,}01}. \quad (8)$$

According to the International Organization for Standardization [11], the distance L is set to be 1000 linear ft, i.e. 304,80 m. In these dimensions, the quantitative estimation of atmospheric dustiness is as follows [2]:

K_{dust} = 0 – 0,9 low; K_{dust} = 1 – 1,9 moderate;
K_{dust} = 2 – 2,9 high; K_{dust} = 3 – 3,9 very high;
K_{dust} = 4 – 4,9 extreme.

To assess the quality of the regression models developed, the coefficient of determination R^2 was used which determines the degree of linear dependence between the regressors involved in the model and the predicted value of the initial variable. The criterion of Fisher is used to check the significance of R^2 [12,13]

$$F = \frac{R^2}{\left(1-R^2\right)}.\frac{\left(N_1 - k\right)}{\left(k-1\right)}, \quad (9)$$

where: k – number of the estimated parameters of the model; N_1 – the size of the sample of experimental data. The Fisher criterion has degrees of freedom $\nu_1 = k - 1$ and $\nu_2 = N_1 - k$.

At $F > F(\alpha, \nu_1, \nu_2) = F_{crit}$, the value of R^2 is considered to be significant and it can be used for estimation of model adequacy. The higher the calculated value of R^2 the more reliable is the regression model.

3. Results and discussion

The present paper describes the development of numerical models for calculation of the visibility using the concentration of PM10 at three monitoring sites in the municipality of Burgas: AMS Meden Rudnik (European code BG0063A), AMS Dolno Ezerovo (European code BG0063A) and AMS Nesebar (European code BG0071A). An important issue for the region is the high levels of PM10 concentration which requires the development of new quantitative methods for studying and controlling the AQI with respect to this critical pollutant for the city.

The regression model (7) for calculation of the visibility includes one factor – the concentration of PM10. The regression coefficients were determined individually for the three monitoring sites (AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar). The data used were daily measured PM10 concentrations on a monthly basis [4].

The regression coefficients obtained with eq.(7) for calculation of the visibility for each site are presented in Table 1.

Table 1. Regression coefficients in eq.(7) for calculating the visibility for each monitoring site

Monitoring site	Model 7
AMS Dolno Ezerovo	$L_{V1} = 1028{,}0182.\dfrac{1}{C_1} + 0{,}386044$
AMS Meden Rudnik	$L_{V2} = 1016{,}8085.\dfrac{1}{C_2} + 0{,}470897$
AMS Neseber	$L_{V3} = 1042{,}0126.\dfrac{1}{C_3} + 0{,}407167$

In Table 1: L_{V1}, L_{V2} and L_{V3} are the visibilities calculated by eq.(6) for the monitoring sites AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar, respectively, *km*; C_1, C_2 and C_3 – daily concentrations of PM10 at the individual monitoring sites.

Table 2 shows the calculated coefficients together with the quality parameters of the corresponding models developed for the individual sites estimated by the Fisher criterion (9).

Table 2. Coefficients and quality parameters of model (7) for the individual monitoring sites

Monitoring site	Coefficients	Standard error	Fisher coefficient F	Coefficient of determination R^2
AMS Dolno Ezerovo	$b = 0.2600$ $a = 0.9892$	0.1386 0.0054	33315.6	0.9893
AMS Meden Rudnik	$b = 0.2540$ $a = 0.9893$	0.1360 0.0052	33657.9	0.9852
AMS Neseber	$b = 0.2114$ $a = 0.9941$	0.1560 0.0040	61681.5	0.9941

It can be seen from Table 1 that the values of the coefficients of determination are very close to unity ($R^2 > 0.98$) which is considered enough to conclude that the models are of good quality and reliability. The values of the F-criterion obtained were higher than the critical value. For instance, the F-criterion for AMS Dolno Ezerovo was calculated to be 33315.6 while the critical value is 2.27. The values of the criterion calculated for the other sites were of similar order.

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The statistical estimation carried out showed that the regression equations derived (7) are reliable enough to be used for prediction of the visibility.

The values of the visibility calculated by formula (6) and the regression models (7) for the three sites (AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar) are shown in Fig.1.

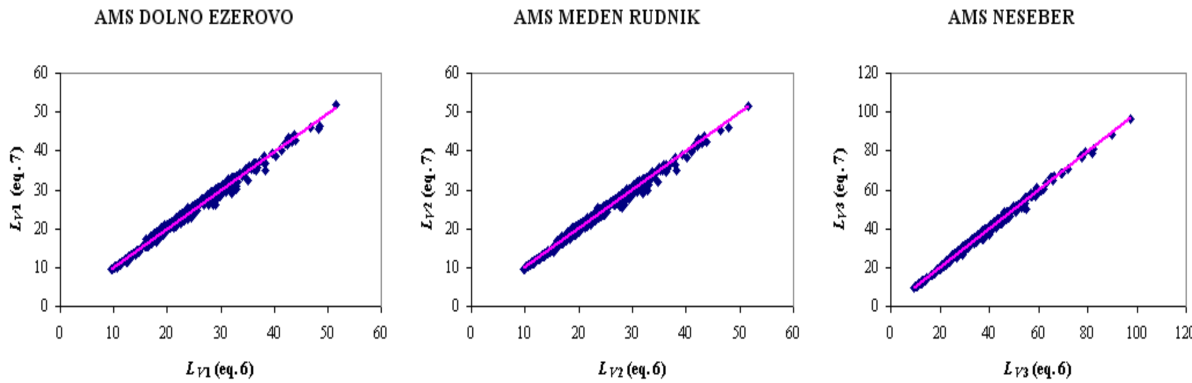

Fig. 1. Values of visibility L_V (eq. 6) and regression models L_V (eq. 7) calculated for the three monitoring sites studied

Table 3. Values of visibility calculated by formulae (6) and (7) on a monthly basis for the three monitoring sites studied and the relative errors ε %

	AMS Dolno Ezerovo			AMS Meden Rudnik			AMS Nessebar		
	L_V, Eq.6 km	L_V, Eq.7 km	ε %	L_V, Eq.6 km	L_V, Eq.7 km	ε %	L_V, Eq.6 km	L_V, Eq.7 km	ε %
Jan	16.06	15.49	3.69	14.81	14.36	3.12	15.83	15.38	2.93
Feb	19.90	19.12	4.10	19.02	18.30	3.92	29.59	28.53	3.71
Mar	21.19	20.54	3.16	21.04	20.40	3.13	30.98	30.06	3.06
Apr	26.64	26.39	0.95	26.43	26.19	0.89	30.63	30.39	0.81
May	30.24	30.66	1.38	30.19	30.57	1.22	43.27	43.72	1.02
Jun	27.94	28.66	2.51	27.44	28.13	2.45	43.41	44.38	2.19
Jul	26.48	27.44	3.52	26.54	27.46	3.38	41.21	42.51	3.07
Aug	23.22	24.13	3.75	22.84	23.73	3.75	35.50	36.80	3.54
Sept	27.79	28.36	2.01	28.22	28.65	1.50	44.59	45.35	1.68
Oct	31.36	31.04	1.03	30.85	30.48	1.22	52.05	51.44	1.17
Nov	22.72	22.47	1.08	22.29	22.07	0.98	30.64	30.36	0.92
Dec	18.03	17.24	4.58	17.37	16.59	4.75	36.00	34.72	3.69

The values of visibility calculated by formulae (6) and (7) on a monthly basis for AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar are presented in Table 3. The relative errors ε % were also calculated.

For all the sites, the relative error was smaller than 5% which is good precision.

Fig.2. shows the values of the coefficient of dustiness K_{dust} calculated by formula (8). Obviously, higher dustiness values were obtained for the winter months. For instance, K_{dust} for January for the three sites was in the range 3 – 3.5 (very high). The coefficient K_{dust} was between 2 and 3 (high) for February, March, August, November and December for AMS Dolno Ezerovo and AMS Meden Rudnik. For the same months, the value of K_{dust} at AMS Nesebar was between 1 and 2 (moderate). For the rest of the months, K_{dust} at AMS Dolno Ezerovo and AMS Meden Rudnik was between 1 and 2 (moderate). On the whole, the values at AMS Nesebar were better than these at AMS Dolno

Ezerovo and AMS Meden Rudnik because the region there is clearer.

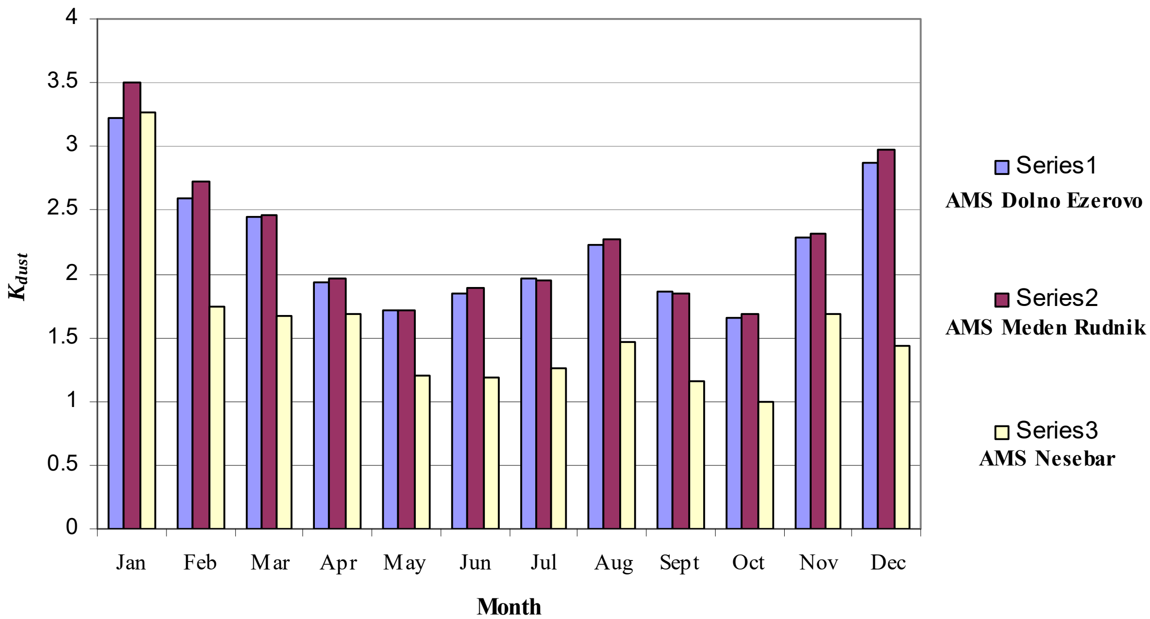

Fig. 2. Coefficients of dustiness K_{dust} calculated by formula (8) for the three monitoring sites studied

The tests and checks carried out showed that the models developed are suitable for quantitative estimation of the relationship between the atmospheric transparency and PM10 concentration in the air.

4. Conclusions

Based on the results and discussion above, it can be concluded that:

The paper reports for models developed for calculation of the visibility on the basis of PM10 concentration at three monitoring sites: AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar. An important issue for the region is the comparatively high levels of PM-10 which makes it necessary to develop new quantitative methods for studying and controlling the air quality with respect to this important for the city atmospheric pollutant.

The regression coefficients in eq.(7) were determined for each monitoring site. The qualities of the models were estimated by the Fisher criterion. The values of the coefficients of determination were very close to unity ($R^2 > 0.98$) which means that the models have good quality and reliability. The values of the F-criterion obtained were higher than the critical one. For instance, the F-criterion for AMS Dolno Ezerovo was calculated to be 33315.6 while the critical value is 2.27= The values of the criterion calculated for the other sites were of similar order. The values of visibility calculated by formula (6) and the regression models (7) for the three monitoring sites (AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar) were compared graphically.

The visibility values were calculated on a monthly basis by formulae (6) and (7) for AMS Meden Rudnik, AMS Dolno Ezerovo and AMS Nesebar. For all the sites, the relative error obtained was smaller than 5% which is good precision.

The values of the coefficient of dustiness K_{dust} were calculated by formula (8). It can be seen that higher dustiness was registered during the winter months. For instance, K_{dust} for January for the three sites was in the range 3 – 3.5 (very high). The coefficient K_{dust} was between 2 and 3 (high) for February, March, August, November and December for AMS Dolno Ezerovo and AMS Meden Rudnik. For the same months, the value of K_{dust} at AMS Nesebar was between 1 and 2 (moderate). For the rest of the months, K_{dust} at AMS Dolno Ezerovo and AMS

Meden Rudnik was between 1 and 2 (moderate). On the whole, the values at AMS Nesebar were better than these at AMS Dolno Ezerovo and AMS Meden Rudnik because the region there is clearer.

The tests and checks carried out showed that the models developed are suitable for quantitative estimation of the relationship between the atmospheric transparency and PM-10 concentration in the air.

The presence of fine dust particles sized 10 □m in the air is a major problem for the municipality of Bourgas. Smaller particles (2.5 □m) also affect the visibility and the coefficient of dustiness but they are not monitored at the sites of the national system for ecological monitoring located in the region.

The object of a consequent investigation will be the concentration of PM-2,5 according to BDS БДС EN 12341:2014 at sites affected by various sources of pollution, as well at sites with the highest expected concentrations.

Since most of the PM-2,5 particles a condensable, a further step could be to study their composition which will provide more information on their light absorption properties.

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