Letter to Editor

Study of Particulate Matter Pollution in Warsaw Area

G. Majewski*, W. Przewoźniczuk

Division of Meteorology and Climatology, Warsaw University of Life Sciences,
Nowoursynowska 166, 02-776 Warszawa, Poland

Received: 3 March 2008
Accepted: 28 November 2008

Abstract

An attempt was undertaken in this work to characterize the imission field of the PM10 particulate matter in the Warsaw area, based on measurements coming from 11 stations located in area, and from 4 stations outside Warsaw belonging to the Voivodship Inspectorate of Environmental Protection in Warsaw. The analysis concerns the 2004-06 period. Basic descriptive statistics of the concentration were calculated, the daily (24 hrs) averaged courses were studied in the whole experimental period for the cold (Oct.-March) and warm (April-Sept.) seasons, rose diagrams of particulate matter concentration percentages and of pollution plume rate percentages were made, and an effort to visualize the spatial distribution of particulate matter over the Warsaw area was made, on the basis of PM10 particulate matter concentration values registered at the stations mentioned above. As a result of the executed analyses it was found that the existing measurement network of PM10 is insufficient for a precise recognition of the imission field. It is necessary not only to extend the network of monitoring stations, especially in the Warsaw districts located on the right bank of the Vistula River, but also to include all vital meteorological parameters and particulate matter qualitative analyses into the range of measurements. In relationship to a high level of PM10 concentrations occurring in the area of the whole city, the authors propose publicizing measurement results. The analysis of pollution plumes, which was possible only for two monitoring stations located in the northern and southern parts of the city, enabled the authors to focus on substantial causes for increased PM10 concentration in that regions.

Keywords: particulate matter PM10, pollution plume, meteorological conditions, Warsaw

Introduction

Air pollution due to particulate matter (PM10) is a substantial and yet unresolved problem in most European countries. This matter is one of the most important air pollutants in relation to which actions are undertaken as defined in the 96/62/EC Directive aiming at the protection of human health. It is placed in the first group of hazardous substances mentioned in Annex I of the Directive. In spite of actions undertaken in many places in Europe, mainly in urbanized areas, PM10 levels exceeding the defined limits occur. Many scientific contributions of both Polish and foreign researchers confirm the significant relationship between the concentration of the small-sized particles and the increase of health risk for inhabitants of urban-industrial centres [1-9]. In particular, epidemiological research and the examination of mutagenic effects of fine matter have proven its prevailing share in the deterioration of human health, because its finest particles can penetrate the deepest lung zones. EPA and WHO reports [10-13] confirm this statement, and they even point out the impact of little, periodical increase of concentration on human population health. According to the CAFE WG report on PM, [11] exposure to particulate matter influence shortens average

*e-mail: grzegorz_majewski@sggw.pl

life expectancy of UE-25 by approximately nine months, which corresponds with 3.6 million years of lost life or about 348,000 cases of early death per year. About one third of the population in Poland exposed to inhaling particulate matter acquires long-term respiratory diseases that lead to illnesses of the circulatory system and, probably, cancer [14].

In Poland the excesses of allowable concentrations of PM10 particulate matter in the air occur over the whole country, especially in big urban and industrial areas in various seasons of the year. The reason is the fact that the structure of energy source utilization in Poland has not undergone substantial change. Black coal continues to be the basic energy source; its share in the national energy market has remained at 50% since 1999, and lignite has 14% of total energy share. The unfavourable coal-based fuel is, among others, the main cause of high emissions of fine particulate matter [15]. Therefore, carrying out costly air conservation programmes on those areas is necessary for decreasing the air pollution threats to human health. The Upper Silesia Industrial Region has priority for restoration actions; the System of Identification of Air Pollution Flows has been working there for several years, making possible not only the identification of emission sources but also the assessment of how various source groups (e.g. sources linked with individual households, traffic sources, etc.) impact air quality in the area of the measurement station. Tracking occurrences of low emission sources coming from the communal sector is a task of the air pollution mission field in Poland.

An attempt has been undertaken in this work to characterize the imission field of the PM10 particulate matter in the area of Warsaw. Measurements of particulate matter concentrations have been carried out in recent years with the use of many measuring methods, differing not only in measuring principle but also in accuracy, sampling frequency and separation of dust fractions. Since 1 October 2003 Warsaw has built a large network for measuring PM10 particulate matter concentrations, consisting of 4 automatic and 7 manual stations. Such a network of measurements makes the monitoring of spatial distribution of this pollution possible, as well as drawing conclusions on relationships between particulate matter concentration and meteorological parameters at those stations.

Material and Methods

The data used in this paper were made accessible by the Voivodship Inspectorate of Environmental Protection in Warsaw in the framework of co-operation. They involved all 11 monitoring stations in the area of Warsaw measuring the concentration of PM10 particulate matter:
MzWarszSGGW(1),
MzWarszBernWoda(2),
MzWarszZeganWSSE(3),
MzWarszBorKomWSSE(4),
MzWarszKrucza(5),
MzWarszZelazWSSE(6),
MzWarszAKrzWSSE(7),
MzWarszUrsynów(8),
MzWarszNiepodlKom(9),
MzWarszBielany(10),
MzWarszTarKondra(11)
and 4 stations outside Warsaw:
MzLegionZegIMGW(12),
MzPiastowPulask(13),
MzOtwockBrzozWSSE(14),
MzPiaseczDworWSSE(15).

The location of the stations is shown in Fig. 3. The data from all 15 stations were used to characterize the imission field, while those from 2 stations, MzWarszTarKondra and MzWarszUrsynów, were used to define pollutant airflow directions, because measurements of basic meteorological parameters is carried out in parallel with that of particulate matter concentration. The measurements of PM10 concentration were made with reference methods at the stations mentioned above according to the requirements included in the order by the Minister of Environment concerning permissible levels of some substances in the air and tolerance margins for permissible levels of some substances (Dz.U. nr 87 z 2002r., poz. 796) [16]. The used methods comply with the norm EN12341.

Table 1. Descriptive statistics of PM10 concentrations from the stations of the Warsaw area in 2002-06.

a)

Label (no.)	MzWarszSGGW (1)			MzWarszBernWoda (2)			MzWarszZegWSSE (3)		
1. Year	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
2. Annual average:	36.9	42.2	34.7	20.4	21.6	30.5	37.6	39.2	36.2
3. Cold season average:	40.2	45.8	41.4	20.6	22.5	35.8	39.9	45.9	44.9
4. Warm season average:	33.7	38.6	28.0	16.8	20.6	25.2	34.8	32.5	27.4
5. S_{24} Min.	3.9	7.8	2.0	4.0	2.0	2.0	4.0	8.0	8.0
6. S_{24} Max.	140.2	158.8	320.8	109.0	78.0	294.0	178.0	155.0	237.0
7. Date of occurrence of S_{24} Max.	29 Jan.	28 Sept.	27 Jan.	3 March	6 Sept.	27 Jan.	11 Dec.	4 March	27 Jan.
8. Number S_{24}> D_{24}	60	84	50	10	12	39	45	79	58
9. Relative differentiation - Z_w (%)	8.8	8.5	19.2	10.1	4.4	17.4	6.8	17.0	24.1

Table 1. Continued.

b)

No.	MzWarszBorKom (4)			MzWarszKrucza (5)			MzWarszZelazWSSE (6)			MzWarszAKrzWSSE (7)		
1	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
2	25.7	35.2	38.9	31.0	41.7	43.6	31.4	32.9	37.7	23.9	31.1	34.3
3	26.2	37.0	43.7	37.1	49.2	53.5	36.8	36.8	47.2	29	38.0	47.3
4	25.4	33.4	34.1	25.0	34.3	33.7	26.1	29.1	28.2	19.7	24.3	25.6
5	4.0	2.0	9.0	5.1	7.0	3.7	9.0	11.0	8.0	5.0	7.0	7.0
6	90.0	111.0	224.0	143.0	162.0	289.0	128.0	89.0	372.0	94.0	120.0	226.0
7	31 Dec.	3 March	27 Jan.	29 Jan.	3 Nov.	27 Jan.	29 Jan.	10 Feb.	27 Jan.	11 Dec.	2 Apr.	27 Jan.
8	16	50	72	48	107	104	36	44	47	10	55	47
9	1.6	5.1	12.3	19.6	17.9	22.8	17.0	11.7	25.3	19.0	22.1	29.8

c)

No.	MzWarszUrsynow (8)			MzWarszNiepodlKom (9)			MzWarszBielany (10)			MzWarszTarKondra (11)		
1	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
2	35.5	32.8	36.5	57.3	51.6	58.7	42.9	37.9	44.6	37.0	32.1	38.8
3	37.5	33.6	41.9	58.5	50.6	64.7	49.6	41.8	32.2	39.7	33.5	45.2
4	33.4	32.0	31.1	56.1	52.7	52.7	34.9	34.1	27.3	34.3	30.7	32.4
*	231.3	500.0	414.9	353.7	472.9	358.1	296.3	-	-	281.3	321.0	566.8
5	6.3	6.3	6.9	16.1	12.8	14.4	11.7	4.7	13.2	11.1	4.8	9.0
6	156.4	102.6	312.0	179.3	125.1	260.4	183.5	120.8	130.5	180.9	131.4	296.3
7	29 Jan.	4 March	27 Jan.	29 Jan.	2 Nov.	27 Jan.	29 Jan.	24 March	10 Jan.	29 Jan.	23 March	27 Jan.
8	60	57	55	211	148	193	88	66	47	62	41	73
9	5.84	2.4	14.85	2.17	-2.04	10.24	17.47	10.18	8.2	7.32	4.4	16.56

*-maximum value 1-h

d)

No.	MzLegionZegrzMGW (12)			MzPiastowPulask (13)			MzOtwockBrzozWSSE (14)			MzPiaseczDworWSSE (15)		
1	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**	**2004**	**2005**	**2006**
2	22.1	22.5	31.1	22.7	24.4	34.6	27.0	35.5	32.2	29.5	37.2	37.1
3	26.1	25.3	33.9	27.0	26.9	38.1	30.4	35.2	36.3	39.8	44.5	43.1
4	18.0	19.6	28.2	18.5	21.9	31.1	23.7	35.9	28.1	25.7	37.3	31.2
5	2.0	2.0	4.0	4.0	4.0	4.0	3.0	6.0	3.0	8.0	4.0	7.0
6	113.0	108.0	219.0	102.0	91.0	135.0	142.0	208.0	227.0	212.0	203.0	243.0
7	28 Jan.	2 Apr.	27 Jan.	28 Jan.	2 Apr.	26 March	29 Jan.	2 Apr.	27 Jan.	29 Oct.	2 Nov.	27 Jan.
8	15	16	44	11	21	50	36	71	65	29	79	65
9	18.32	12.7	9.23	18.68	10.29	10.14	12.51	-1.04	12.78	21.44	8.78	15.9

S_{24} – average daily concentration [$\mu g \cdot m^{-3}$];
D_a – average permissible yearly concentration [$\mu g \cdot m^{-3}$]; $D_a = 40\ \mu g \cdot m^{-3}$,
D_{24} – average permissible daily concentration [$\mu g \cdot m^{-3}$], $D_{24} = 50\ \mu g \cdot m^{-3}$,

$$S_Z(\%) = \frac{S_Z}{S_L + S_Z} \cdot 100\% \quad S_L(\%) = \frac{S_L}{S_L + S_Z} \cdot 100\%$$

$Z_w(\%) = S_Z(\%) - S_L(\%)$ where: S_Z – PM10 concentration [$\mu g \cdot m^{-3}$] in cold season, S_L – PM10 concentration [$\mu g \cdot m^{-3}$] in warm season
Z_w – relative differentiation of PM10 concentration between cold and warm half-years [%].

The first step in the analysis of the collected data refers to:

1. descriptive statistics, such as:

- PM10 particulate matter concentration values – monthly, half-year (warm [April-Sept.] and cold [Oct.-March]) and annual ones,
- the variability range of PM10 concentration values, the dates of occurrence of maximum values, the number exceeding the allowable limit as well as 1-hour maximum value of concentration registered at automatic stations,
- relative differentiation of PM10 concentrations between cold and warm half-years (Table 1).

The values of average yearly and daily concentrations of dust were compared to the allowable levels published by the Ministry of the Environment after adaptation to European standards. The allowable norm for average yearly concentration in Poland is at present Da = 40 $\mu g \cdot m^{-3}$, and the average daily concentration is D24 = 50 $\mu g \cdot m^{-3}$, with an allowable exceedence of 35 days in a year. That value, according to the EU directive, was 65 $\mu g \cdot m^{-3}$ in 2002, 60 $\mu g \cdot m^{-3}$ in 2003, and 55 $\mu g \cdot m^{-3}$ in 2004.

Next, the characteristic of PM10 imission field in the area of Warsaw involved:

2. searching out the daily course of particulate matter concentrations in both warm and cold half-years on the basis of the collected data,

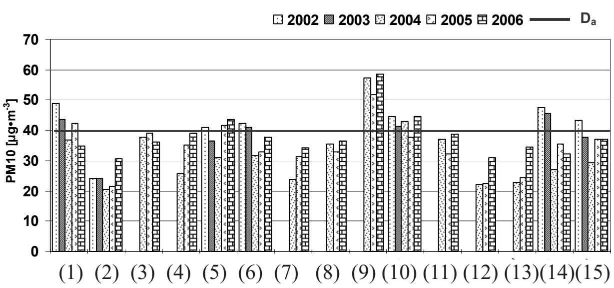

Fig. 1. Average yearly values of PM10 [$\mu g \cdot m^{-3}$] at the stations of the Warsaw area in the years 2002-06.

3. preparing maps of spatial distribution of particulate matter concentration values by the Surfer programme.

The work also aimed at:

4. identification of air flow directions over the Warsaw area studied and an attempt to identify the sources of PM10 in the region mentioned.

Preparation of pollution roses was introduced to attain this goal. This method allows us to find which wind directions are associated with the highest concentrations. However, a relatively high value of pollution concentration may result from incidental occurrence of elevated values of pollution in a given sector. Rose diagrams of suspended particulate matter concentration percentiles give a better graphic visualization [17].

Studies on air flow in the area of Warsaw incorporated the PM10 plume rates, which were analyzed to gain information on particulate matter imission pattern over the area and its intensity [18, 19]. The plume rate is a vector. The scalar value of this vector is equal to the pollution quantity flowing in a time unit through the unit area normal to flow direction.

In this paper, the plume rate value was approached as a product of mean pollutant concentration and mean wind vector for each measurement period [17, 20].

This plume rate [$\mu g \cdot m^{-2} \cdot s^{-1}$] is then a measure of inflow or outflow of substance through the unit surface in space [20]. The analysis of PM10 plume rates was possible only in a case when the velocity and the direction of wind were registered in parallel with pollution concentration measurements. Only two stations fulfilling that condition were found within the PM10 monitoring network in the Warsaw area: MzWarszUrsynów situated in the southern part of the city and MzWarszTarKondra in the northern one. Using the data from those stations the following results were prepared:

- rose diagrams of PM10 concentration percentiles, rose diagrams of PM10 plume rate percentiles.

After calculating the pollution plume rates, rose diagrams of their percentiles were prepared in the range p = 50, 60, 70, 90, 95, 98. If high pollution concentrations and high pollution plume rates occur in the same inflow sector at the same time, then we can state that point sources of great emission concentration are a reason for high pollution concentrations.

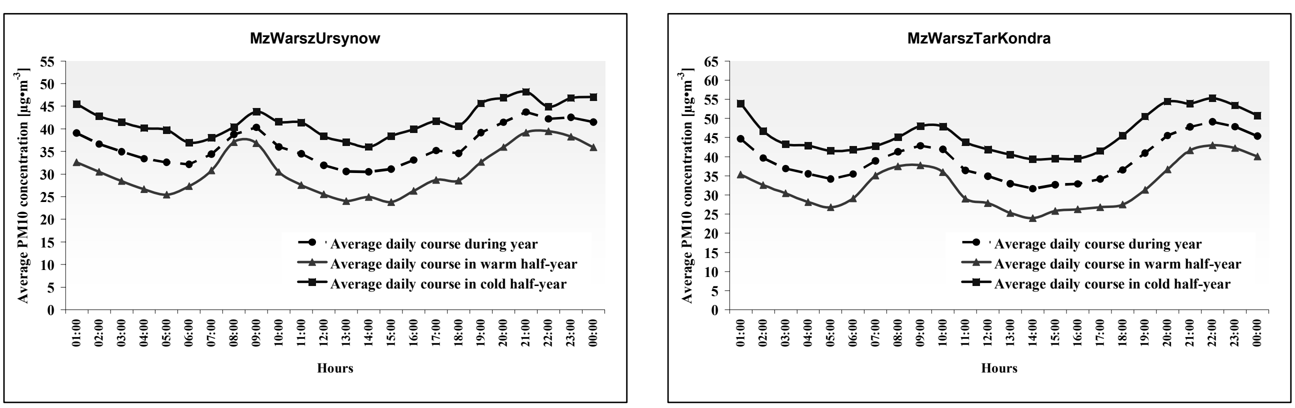

Fig. 2. Average daily course of PM10 concentration values in 2006, at stations MzWarszUrsynow and MzWarszTarKondrat, considered representative stations for urban imission patterns.

Otherwise, when high pollution concentrations occur in the sector, but pollution plume rates are low, then sources of low emission concentration situated a little distance from the station are the most probable cause for the higher values of pollution concentrations.

To make rose diagrams of PM10 plume rate percentiles, the area around two stations under study were divided into two equal sectors with central angle α, constituting 1/16 of the round angle. Based on pollution plume rate value sets occurring at the inflow of air from the direction in a given sector α, percentiles p = 50, 60, 70, 90, 95, 98 were calculated. Rose diagrams were made for all wind direction percentiles; they present visual pictures of the distribution of pollution plume rate values [17, 21].

Results and Discussion

Descriptive Statistics

Descriptive statistics of suspended PM10 concentrations for the stations in the Warsaw area in the period 2004-06 are presented in Tables 1a, 1b and 1c. The following features were presented in those tables: values of minimum and maximum concentrations, maximum value occurrence date, numbers of exceeding the allowable value, and relative differentiation; maximum 1-hour concentrations were presented for automatic stations. This results from both tables and Fig. 1 that the permitted norm for the average annual PM10 concentration was exceeded at the stations located downtown, near traffic avenues and in densely populated quarters of Warsaw. The farther from the centre of Warsaw, the lower the average yearly concentration values. The number of allowable average exceeding daily concentrations was lower, too. The average annual concentration attained the highest value on the MzWarszNiepodlKom station for all the years under study.

The stations taken into account in this paper were specific with average values of PM10 concentrations being in the cold half-year higher than in the warm one in 90% of cases. There was less differentiation in the stations located downtown at the stations located farther from the city centre and outside it. It is worth mentioning that in principle there is a lack of differentiation of particulate matter concentration values between both half-years (Zw in the interval: -2.04 ÷ +10.2%) at the traffic station in the very centre of Warsaw (MzWarszNiepodlKom), and a high dust concentration caused certainly by car traffic all year round (the station is located in a street canyon).

The comparison of maximum average daily pollution concentration values leads to interesting findings. The S_{24hmax} occurred in January 2006 at all stations, both urban and peripheral. This is certainly connected with exceptional weather conditions that dominated at that time in Poland and Europe. A large system of high pressure impacted the weather through the greater part of January 2006, the air temperature attained exceptionally low values ($T_{min.}$-26.0°C, $T_{śr.}$ -8.0°C) and the wind velocity was lower than the multi-year average [22]. An increase of both artificial heat emission and air pollution concentration was certain to happen in such conditions.

Daily Course of PM10 Concentration

Average yearly and half-yearly daily courses of PM10 concentration values at two automatic stations are presented in Fig. 2. The occurrence of two clear maximums:

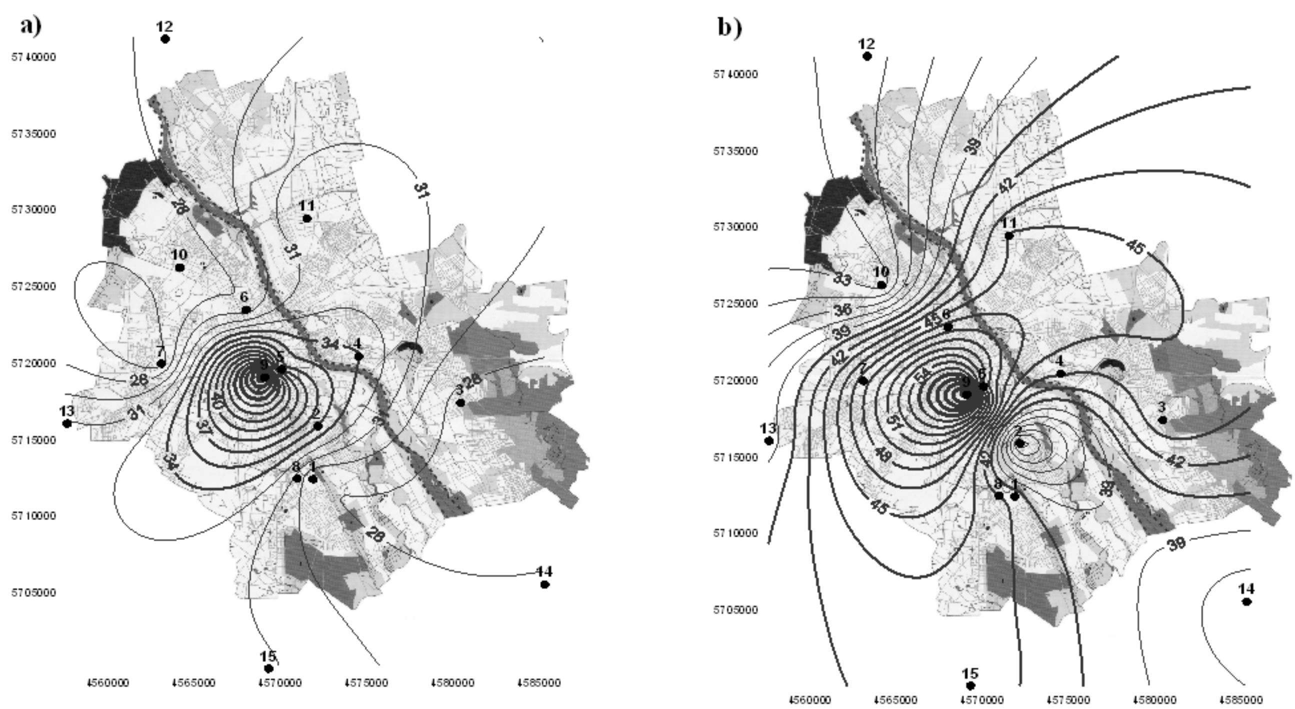

Fig. 3. Maps of average PM10 [$\mu g \cdot m^{-3}$] concentration value distributions in the Warsaw area for 2006; 1,2...15 – station number; a) warm season, b) cold season

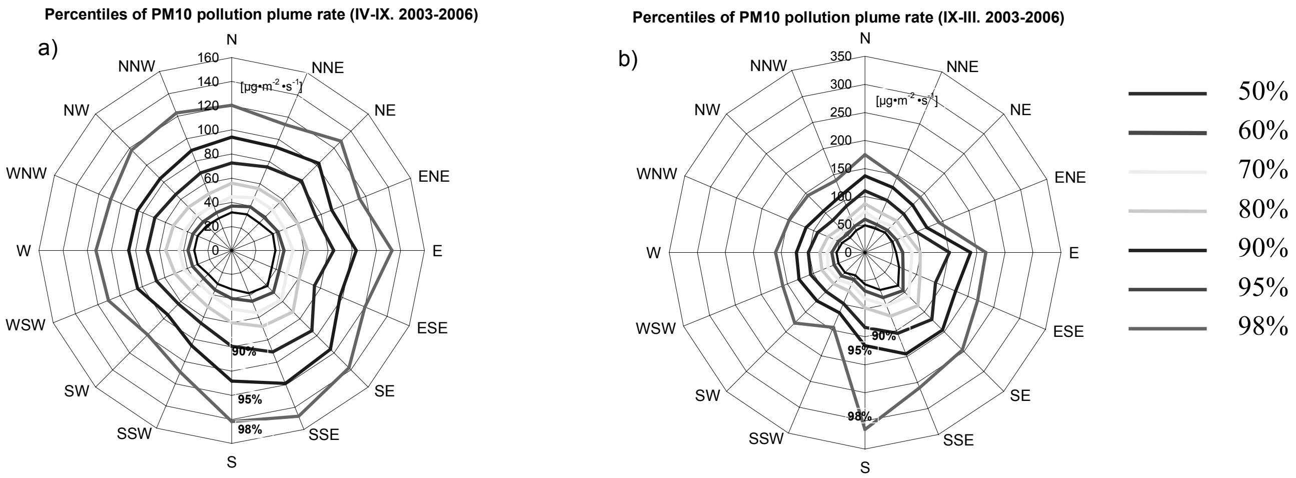

Fig. 4. Rose diagrams of PM10 plume rates in the warm (a) and cold (b) seasons (half-year) on the MzWarszTarKondra station from Oct. 2003 to Dec. 2006.

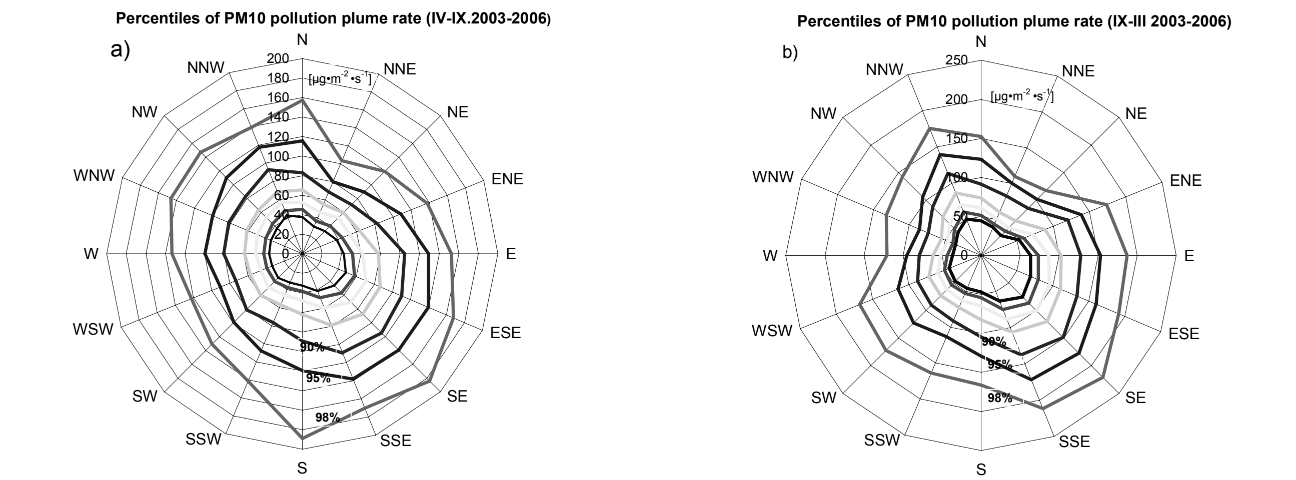

Fig. 5. Rose diagrams of PM10 plume rates in the warm (a) and cold (b) seasons (half-year) on the MzWarszUrsynow station from Oct. 2003 to Dec. 2006

a weaker one in the hours 9-19 a.m. and another one stronger at 18-21 p.m., is a characteristic feature of these courses in both warm and cold half-years, with higher absolute values of concentrations in the cold half-year. Two distinct drops of values (one in the early morning till sunrise and another at near-noon hours) also occur in the daily course of PM10 concentration. Such a daily concentration course results from the course of daily pollution emission to the atmosphere (traffic peaks, fuel combustion processes in low communal sources) and from the daily cycle of mixing layer thickness change connected with the development and disappearance of the convection processes.

Spatial Distribution of Suspended Particulate Matter Concentration Values in the Warsaw Area

The spatial distribution of suspended particulate matter concentration values in the Warsaw area is presented in Fig. 3. In both warm and cold seasons the greatest amount of suspended particulate matter occurs in Warsaw's centre on the western bank of the Vistula River, and the dust concentrations decrease very quickly when moving away from it. However, the small number of stations does not allow more precise presentation of dust distribution on the right bank of the Vistula. There is then a necessity for extending the measurement network in that area.

Identification of Directions of Air Inflow over the Area of Two Stations in Warsaw, and an Attempt to Indicate Emitters Polluting the Air with PM10 in the Region

The rose diagrams of PM10 plume rate percentiles are presented in Figs. 4 and 5. The differences in plume rates are seen in individual sectors of wind direction on both stations in the cold seasons with heating on. The plumes from the 90-180ºN angle range, that is the eastern-southern sector, are outstanding at the MzWarszTarKondra station located in the northern part of Warsaw, with a clear maximum at the air inflow from the 180ºN sector – that is the southern direction. The distribution of 50 and 70 percentiles of plume rates is almost even in relation to air mass inflow directions. The distribution of the 98 percentile points out to an extremely strong plume of dust inflow from the southern direction, has a rate almost twice as high (over 300 $\mu g \cdot m^{-2} \cdot s^{-1}$) as at the inflow from western sectors. The average plume rates coming from the 90-180ºN sector were 60% higher than those from the other ones. The distribution of PM10 concentration percentiles was similar as above, but not presented here due to the limited content of the paper.

When identifying the inflow directions with rectilinear trajectories one can state that they delineate areas where pollution sources of great emission concentration are located [19]. It results from emission sources being in possession of the authors of this paper that the following power plants are situated in that region, among others: Elektrociepłownia (heat and power generating plant) Siekierki, Polskie Zakłady Optyczne S.A., Stołeczne Przedsiębiorstwo Energetyki Cieplnej S.A., Zakład Energetyki Cieplnej GIGATERM, Elektrociepłownia Kawęczyn, BEHATON Ltd, and MASFALT Ltd.

In the warm season the distribution of dust plume rate percentiles looks quite different. First of all, it is almost even; a small domination of plumes from the 90-180ºN sector is seen, and their rates surpass only by about 15% the concentrations coming from other sectors, with values twice lower than in the winter season. Emission sources of another kind and other conditions of pollution dispersion than in the cold season have shaped the imission field of PM10 particulate matter in this region in the warm season. In the warm half-year (April-Sept.) the heating industry emits less pollution, and weather conditions do not favour the transportation of pollution over a long distance, then the dust imission field is shaped mainly by local sources, at a considerable share from industry and traffic.

Another situation occurs at the MzWarszUrsynow station located in the southern part of Warsaw. The relative differentiation between seasons presented in Table 1 was relatively little. This is also seen in rose diagrams of dust plume rate percentiles. The percentile value distribution in individual wind direction sectors is rather even, and the plume rate values in the cold half-year are considerably higher (about 20%) than in the warm one. In the cold half-year the highest plume rates occur at the air mass inflow from the 90-160ºN sector, surpassing by about 20% the plume rates from the 200-340ºN sectors. Such a distribution of particulate matter plume rate percentiles (almost overlaying the concentration percentile distribution analyzed by the authors [23]) may confirm the impact of sources dispersed around the station on the level of imission in the vicinity of the considered one. Those can be local heating plants or individual home boiler furnaces. The low sources, in spite of their lower impact range and rather local importance, still constitute a considerable threat to health. This threat results especially from the fact that they are situated near human settlements, therefore inhaled dust aerosol with a high share of fine particles are dangerous to human health.

In the warm season the particulate matter plume rate percentile distribution of 50-75% in size was uniform in all the sectors. The 98 percentile course points out to a slightly greater rate of pollution inflow from N and S directions, but it is only about 10% higher than the rate in the rest of sectors. Then, a conclusion can be drawn that in the warm season dispersed sources with small emission rates and nearby traffic had a dominating impact on the particulate matter imission field in the Ursynow station area.

Conclusions

- The permissible norms of PM10 particulate matter concentration are exceeded at the stations in the centre of Warsaw and in densely populated quarters located outside the city centre; this rather high level of concentrations lasts constantly regardless of the season.
- Regarding unfavourable action of fine dust particles on the environment and human health, qualitative measurements of particulate matter should be carried out on those stations and proper monitoring of air condition should continuously be carried out, with transmission of measurement results to the public.
- The analysis of suspended particulate matter plume rates showed that the sources of great emission concentrations, such as Elektrociepłownia Siekierki, Polskie Zakłady Optyczne S.A., Stołeczne Przedsiębiorstwo Energetyki Cieplnej S.A., Zakład Energetyki Cieplnej GIGATERM, Elektrociepłownia Kawęczyn, BEHATON Ltd, and MASFALT Ltd., impacted the dust-laden air in the MzWarszTarKondra station area in the winter season. Reversibly, local sources of low emission concentration, urban traffic and transport shaped the imission field in the warm season.
- Local heating furnaces situated in the vicinity of the MzWarszUrsynow station, especially to be southeast and northwest, influenced mainly the level of concentrations registered at the station in both warm and cold seasons.
- To be able to analyze pollution plumes over the whole Warsaw agglomeration, one should extend the range of measurements with meteorological elements at all monitoring stations.
- The PM10 particulate matter measuring network existing since 2003 is not sufficient yet for getting exact knowledge on the imission field of this pollution, and it should also cover with its range the right-bank part of the city.

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