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Application of Cluster Analysis in Defining the Meteorological Conditions Shaping the Variability of PM10 Concentration

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1. Introduction

Particulate matter is a complex mixture of solid, liquid and gaseous particles which, due to high degree of dispersion, can linger suspended in atmosphere for a long time. Two main fractions of particulate matter are commonly distinguished: PM10 – with a diameter of particles less than10 µm, and PM 2.5 – with a diameter of particles less than 2.5 µm. The fractions differ not only in particle diameter, but also in the process of its origin, chemical composition and half life time.

The concentrations of both fractions they are being closely monitored in Poland as well in Europe due to negative health effects they may cause. The results of air quality monitoring serve as a basis for assessing air quality and spatial variability of air quality [22, 26, 28, 29]. According to recommendations of the Directive of the European Parliament and of the Council CAFÉ [8], the numerical methods for modelling of air pollution dispersion [17] are also used in order to research into the reasons behind violation of admissible standards of particulate matter concentration, including identification of individual sources or sectors of emission responsible for excessive concentrations.

Recent Report of the Inspection of Environment [26] indicates that excessive concentrations of PM10 are recorded in many regions of the country. It results from still high share of solid fuels in the structure of basic primary energy carriers in Poland, as well as the high share of ground level emission. Because of better ventilation conditions in the northern and central part of Poland smog episodes are not problematic yet in the southern part of Poland, particularly in not-easily ventilated basins and well-developed river valleys, smog episodes occur with greater frequency [25].

Apart from emission, air quality is additionally determined by meteorological factors [4, 7, 18, 27, 31]. The effect of weather can be seen in the formation of the dispersion of pollutants and in the rate of disposition. The level of pollutants dispersion depends on, among other things, the dynamics of air movement which is governed by anemometric conditions and thermal stratification within the atmospheric boundary layer. Concentration is also determined by the types of air mass [12] and type of circulation – as has been demonstrated in Małopolska and Górny Śląsk [19, 20, 30]. Precipitation also plays a significant role in the shaping of aerosanitary conditions. According to Czarnecka and Nidzgorska-Lencewicz [5], in the period of 2005–2007, mean concentration of PM10 particulate matter recorded in a series of hours and days with precipitation were, depending on a season and day, by 10–35% smaller than concentrations recorded before the precipitation occurred.

The research on the relationship between air quality and meteorological conditions makes use of various statistical methods such as: correlation, regression, cluster analysis and principal components analysis [4, 6, 9, 11, 16, 23, 31, 33]. The aim of the present paper is to single out the set of meteorological elements which affect the variability of PM10 concentration in the area of Tricity agglomeration in six winter seasons from 2004/2005 to 2009/2010, with the use of cluster analysis.

Only PM10 fraction is taken into consideration in this paper as the obligatory monitoring of PM2.5 particulate matter, as regulated by the Directive 2008/50/WE [8] of 21 May 2008, was introduced in Poland as late as at the beginning of 2010.

2. Materials and methods

Maritime industry is the basis for development but also the main source of pollution in Tricity. The metropolitan area is polluted by shipbuilding industry comprising seven shipyards, including the two largest located in Gdańsk and Gdynia, as well as seaports with ongoing production and services business. Air quality is additionally greatly affected by electrochemical and petrochemical plants, as well as food industry. Additionally, as in every metropolitan area, road transport and power and heat facilities represent important sources of air pollution.

The materials used in this study comprise measurements of immission and basic meteorological elements including air temperature, relative humidity, atmospheric pressure as well as wind speed and direction recorded during the calendar winters (December–February) in the period of 2004/2005–2009/2010. Data was obtained from five automatic air quality measuring stations located in the Tricity agglomeration and was provided by the Agency of Regional Air Quality Monitoring in the Gdańsk Metropolitan Area (**ARMAAG**). The locations of the measuring stations are shown in Fig. 5. Detailed information regarding the methodology of the measurements and elaboration of data is given at http://armaag.gda.pl/. The project of the ARMAAG monitoring network was developed under supervision of Jerzy Trapp, PhD. from the University of Gdańsk and based on longstanding research on meteorological conditions, population density and data on emission from point and surface sources. Monet software obtained by courtesy of the Politecnico di Milano and positively assessed by the Institute of Environmental Protection [34] was used in the project. All the stations located in five districts of Tricity are defined as urban background stations. However, two of them (Gdańsk Wrzeszcz and Gdynia Pogórze) are located in residential areas, and the station in Gdańsk Jasień is located in the vicinity of scattered, low-building housing developments next to the Tricity ring road. Sopot station is located in allotment area, and the station in Gdynia Śródmieście – on the harbour waterfront.

The cluster analysis method was used to estimate the amount and variability of PM10 particulate matter immission with respect to meteorological conditions. Prior to the analysis, all baseline data was standardised according to the formula [21]:

$$z = \frac{x - \bar{x}}{s} \tag{1}$$

where:
x – non-standardised variable,
$\bar{x}$ – arithmetic mean,
s – standard deviation.

Such transformation allows for comparison of values of many variables, regardless of their original distribution and units of measurement. As a result of standardisation all variables were in the range of 0 to 1.

Hierarchical clustering is used most commonly in studies on air quality [2, 6, 31, 33]. However, in this paper we use the *k*-means clustering (Euclidean distance), which belongs to a group of non-hierarchical cluster analysis methods. The mechanism implemented in STATISTICA software is based on the v-fold cross-validation, and allowed for identification of the optimal number of segments which are combinations of immission and meteorological elements. However, wind directions based on octagonal compass rose constituted a qualitative change in this analysis. K-mean clustering consisted in transferring the observations from one cluster to another in order to maximise the variations between individual clusters and at the same time minimise the variations within the analysed clusters. The significance of differences between singled out clusters was calculated with the use of analysis of variance – Fisher's test, at the level of $p \leq 0.05$.

The complex influence of meteorological conditions on the variability of particulate matter concentration in selected clusters was determined by linear multiple regression, using a stepwise procedure, at the significance level $p \leq 0.05$. The contributions of individual weather elements in explaining the size of the concentrations were determined using the partial regression coefficients. All calculations were performed using the STATISTICA 10 software.

3. Results and discussion

The winter seasons in the years 2004–2010 were characterized by contrastive thermal conditions (Fig. 1). Only in two of the winter periods, namely in 2005/2006 and 2009/2010, mean temperature of the three winter months (December–February) was below 0°C and amounted to -1.7 and -2.5°C respectively. Moreover, it was well below the average. The temperature in the remaining winter seasons was above 0°C, and two winter seasons (2006/2007 and 2007/2008) were particular ly warm with mean temperature over 3°C. The variability of mean temperature recorded in Tricity metropolitan area during the three winter months amounted to approximately 2°C – Sopot being the warmest district and Gdańsk

Jasień the coldest. The distribution of PM10 concentration in the six analysed winter periods markedly indicates the influence of heating on the variability of pollutants concentration. In two cold winter periods mean concentrations of PM10 exceeded 40 μg·m^{-3}, whereas in the overly warm winter periods the concentration was two times lower (Fig. 1).

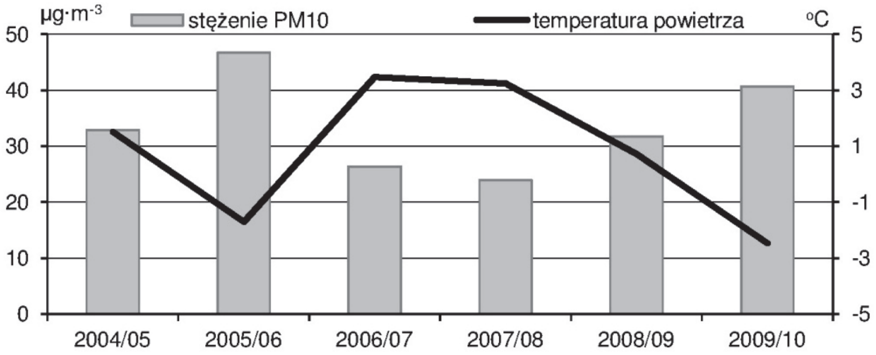

Fig. 1. Average seasonal (December-February) the concentration of PM10 and the air temperature in the Tricity urban area
Rys. 1. Średnie sezonowe (grudzień–luty) stężenia pyłu zawieszonego PM10 oraz temperatury powietrza w Trójmieście

As shown in Fig. 2, in almost all winter seasons the daily limit of PM10 concentration was exceeded. Violation of air quality standards due to abnormal concentrations of PM10 is a problem not only in Poland. According to the *Air Quality in Europe* Report [10], Poland is located in a region where high concentrations of PM10 are recorded more often than in Western Europe.

The highest number of the violations of the standard daily PM10 concentrations were recorded in the two coldest winters, that is in the winter of 2005/2006 and 2009/2010. In the winter of 2005/2006 the standard PM10 concentration was exceeded in approximately 20–40% of cases, and in the winter of 2009/2010 in 20 to almost 50% of winter days, depending on the district of Tricity. In the winter of 2005/2006 the PM10 concentrations standards were exceeded in all districts in January, whereas in the winter of 2009/2010 in various months. Gdynia Śródmieście was the district in which PM10 concentrations standards were exceeded most often. In comparison with the other districts, the winter of

2008/2009 was marked with frequent violation of PM10 concentration standards and even in relatively warm seasons, namely 2006/2007 and 2007/2008, the standards were violated on more than 20 days. The only instance when the PM10 concentration did not exceed the standard was in the winter of 2008/2009 in Gdańsk Wrzeszcz district.

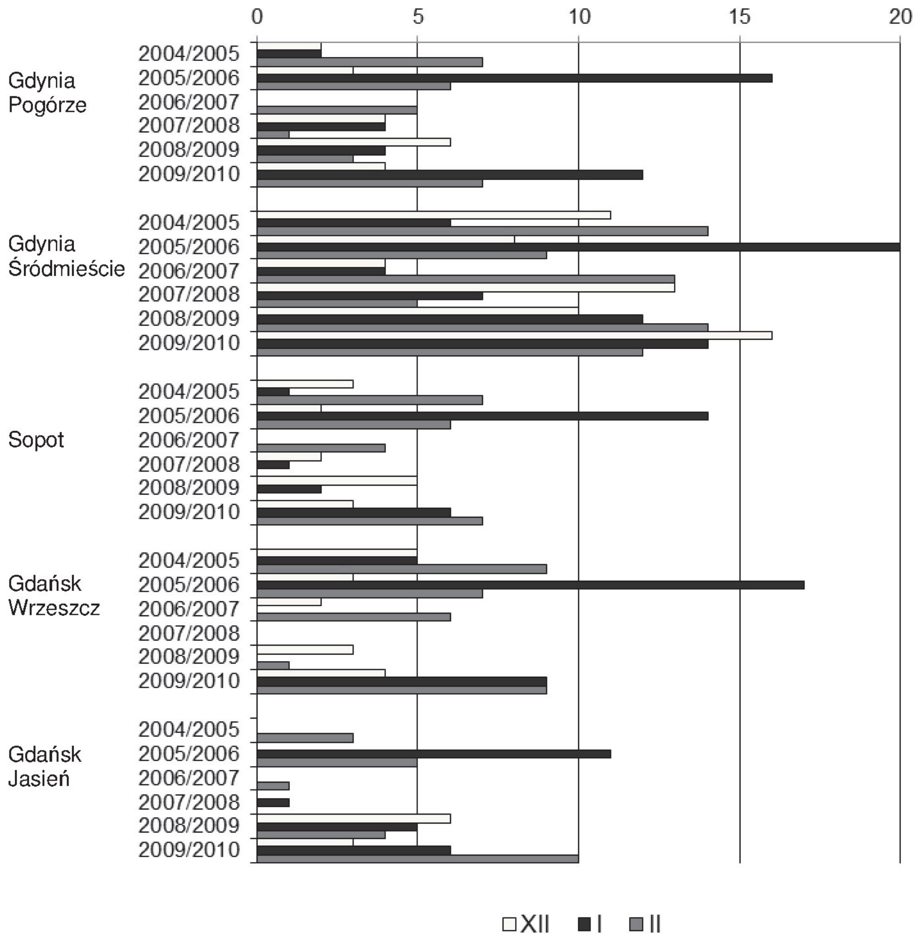

Fig. 2. Number of days with violations of the acceptable mean daily particulate matter (PM10) concentration (50 μg· m^{-3}) during December-February in years 2004/05–2009/10

Rys. 2. Liczba dni z ponadnormatywnymi dobowymi stężeniami (50 μg·m^{-3}) pyłu zawieszonego PM10 w okresie XII–II w latach 2004/05–2009/10

The factor which definitely contributes to the spatial variability of air quality is the wind which causes pollutants transport in the atmosphere. Directional compass roses presented in Fig. 3 show the wind field deformation caused by local factors such as the height of the buildings, distribution, exposure and distance between buildings, transport network or green areas [32]. Only in two districts of Tricity, i.e. Gdynia-Śródmieście and Gdańsk-Jasień, located respectively at the northernmost and south-westernmost outskirts of the agglomeration, W and SW winds prevailed. This is a characteristic feature of the open terrain of the entire region of Pomerania [1]. Due to the specific location of the station in Sopot, among low-building, densely developed, detached-house areas, on the west side of the city, and single health-resort buildings and sports facilities, to the east, the most frequently recorded winds were S-SW-SE. In Gdańsk Wrzeszcz, SE winds were predominant, and N and SE winds were reported with a similar frequency in Gdynia Pogórze. On average, the winds reached higher speeds in the districts where west winds prevailed. The coldest and the warmest parts of Tricity also exhibited contrasting wind speeds. By far the highest average winter wind speed, namely 3.3 m $s^{-1,}$ (with the lowest frequency of calms) was noted in Gdańsk Jasień, while the lowest, i.e. 2.1 m·s^{-1}, in Sopot. Calm weather usually occurred in Gdynia, with a frequency of 3.7% in both districts, while in the other parts of Tricity calms were recorded more than twice less often.

The basic values classified according to the spatial clustering method included sets of hourly measurements of PM10 concentration and meteorological data with the qualitative variable of wind direction. The results of the adopted cluster analysis are presented in Tab. 1, 2, and Fig. 4. The applied algorithm has identified, depending on the area, from 4 to 8 optimal clusters. On average, individual clusters were characterized by different wind directions, occurring with greater and even dominating frequency in comparison to other wind directions recorded in a given district (Tab. 1). Variable wind directions occurring with greatest frequency were characteristic for all identified clusters in Sopot and Gdańsk Wrzeszcz districts. In the remaining three districts of Tricity the cases with the same and most frequent wind directions were included as parts of some clusters. In Gdynia Pogórze NE winds were included into two different clusters (2 and 6); in Gdynia Śródmieście SW winds were included into clusters 3 and 7, and in Gdańsk Jasień W winds to clusters 1 and 4. In almost all identified clusters other wind directions were also observed apart from the main wind directions, yet in most districts the wind direction which was included into other clusters was N wind and additionally NW wind in Sopot and Gdańsk Wrzeszcz. The greatest variation of wind direction in all clusters was observed in Gdańsk Jasień. Winds from N-SE sectors and SW winds were included in every cluster in that district. In Gdynia Pogórze, each of the six clusters included additional E, SW and W winds. The only cluster which grouped conditions connected with S winds, was found in Gdynia Śródmieście.

The characteristics of particulate matter concentrations and meteorological factors in selected clusters are shown in Table 2. The volume of the analyzed meteorological elements in particular clusters generally reflect their well-known role in the shaping of variability of PM10 concentrations. Clusters grouping the highest or elevated particulate matter concentrations in Tricity districts were characterized, in most cases, by the lowest air temperature and lower wind speed, the greatest share of calm – conditions characteristic for a high-pressure weather. Low air temperature contributes to the intensification of district heating based on the use of traditional energy carriers, and to an increase in the emission of the conventional fuels combustion products from local coal-burning heating plants and household furnaces. Moreover, calms, mild winds and frequent inversion layers characteristic for anticyclonic weather limit the vertical and horizontal air ventilation. The increase in pollution concentration in high-pressure weather was demonstrated by Kukkonen et al. (2005), Czarnecka, Nidzgorska-Lencewicz [4], Juda-Rezler et al. [15] Unal et al. [31].

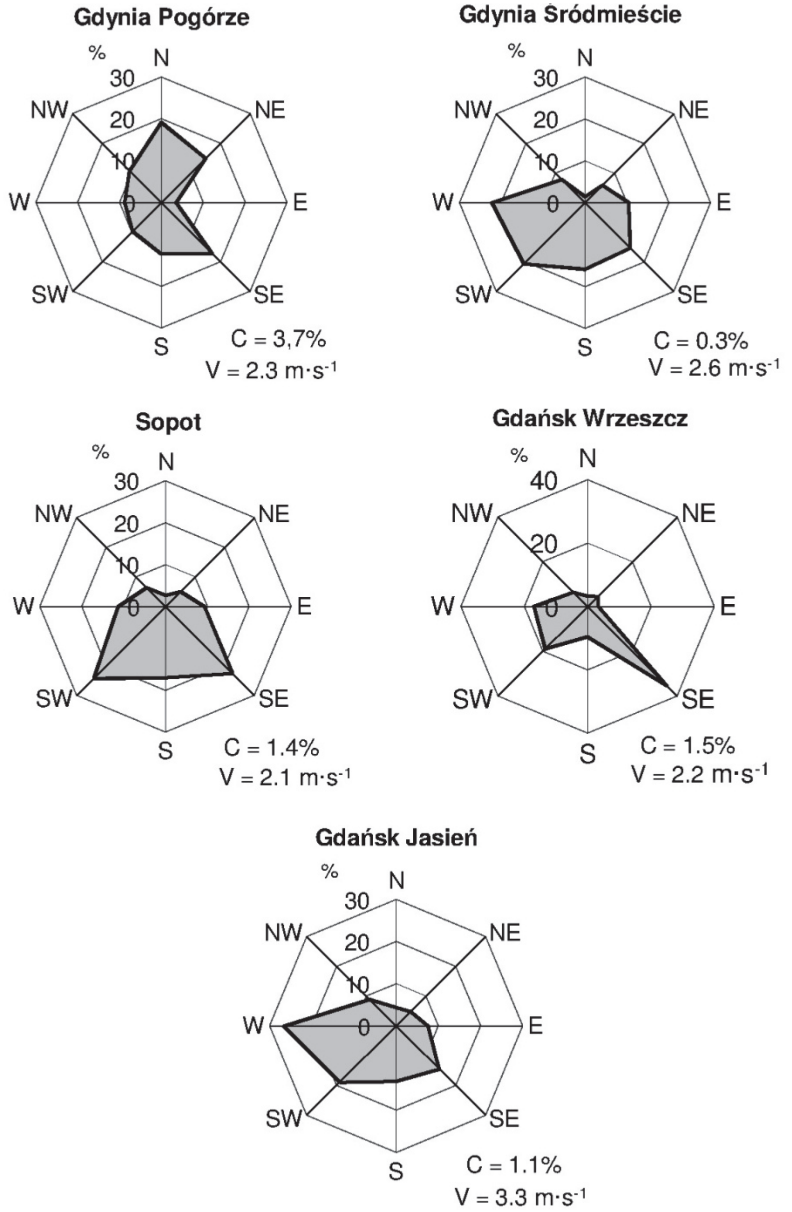

Fig. 3. Characteristics of anemometric conditions in the Tricity urban area during calendar winters (December-February). Years 2004/05–2009/10
Rys. 3. Charakterystyka warunków anemometrycznych w aglomeracji trójmiejskiej w okresie kalendarzowej zimy (XII-II). Lata 2004/05–2009/10

Table 1. Frequency (%) of wind directions and calms in distinct clusters
Tabela 1. Częstość występowania (%) kierunków wiatru i cisz atmosferycznych w wyróżnionych skupieniach

station	cluster	wind directions								calm
		N	NE	E	SE	S	SW	W	NW	
Gdynia Pogórze	1	·	·	0.3	·	·	2.3	1.4	10.8	·
	2	·	9.9	0.8	·	·	3.3	2.4	·	2.6
	3	·	·	0.7	17.3	·	0.1	0.3	·	·
	4	19.0	·	1.0	·	·	0.9	2.2	·	0.2
	5	·	·	0.8	·	12.3	2.0	1.7	·	1.0
	6	·	5.1	0.1	·	·	1.2	0.8	·	·
Gdynia Śródmieście	1	0.2	·	·	·	·	·	23.1	·	·
	2	0.2	6.0	·	·	·	·	·	·	·
	3	·	·	·	·	·	11.2	·	·	·
	4	0.1	·	·	·	14.9	·	·	·	·
	5	·	·	11.7	·	·	·	·	·	·
	6	0.1	·	·	·	·	·	·	8.0	·
	7	0.5	·	·	·	·	8.1	·	·	0.2
	8	0.1	·	·	15.5	·	·		·	0.1
Sopot	1	0.3	0.9	9.3	·	·	·	·	0.4	·
	2	0.2	0.3	·	·	16.9	·	·	0.7	0.1
	3	0.4	0.6	·	22.5	·	·	·	0.6	1.2
	4	0.5	0.8	·	·	·	·	·	1.7	0.1
	5	1.3	2.5	·	·	·	24.3	·	3.0	·
Gdańsk Wrzeszcz	1	0.5	·	·	35.4	·	·	·	0.3	·
	2	1.2	·	3.5	·	·	·	·	1.3	1.2
	3	0.1	·	·	·	·	18.9	·	0.7	·
	4	0.8	4.5	·	·	·	·	·	2.4	0.1
	5	0.1	·	·	·	·	·	17.0	0.5	·
	6	0.6	·	·	·	9.6	·	·	1.2	0.2
Gdańsk Jasień	1	0.6	1.1	2.6	3.5	·	2.0	10.8	·	0.7
	2	1.4	2.0	2.5	3.7	12.5	2.7	·	·	·
	3	1.6	1.2	2.6	5.6	·	4.6	·	9.0	0.4
	4	0.7	0.7	0.2	1.7	·	9.0	16.4	·	·

· not occur

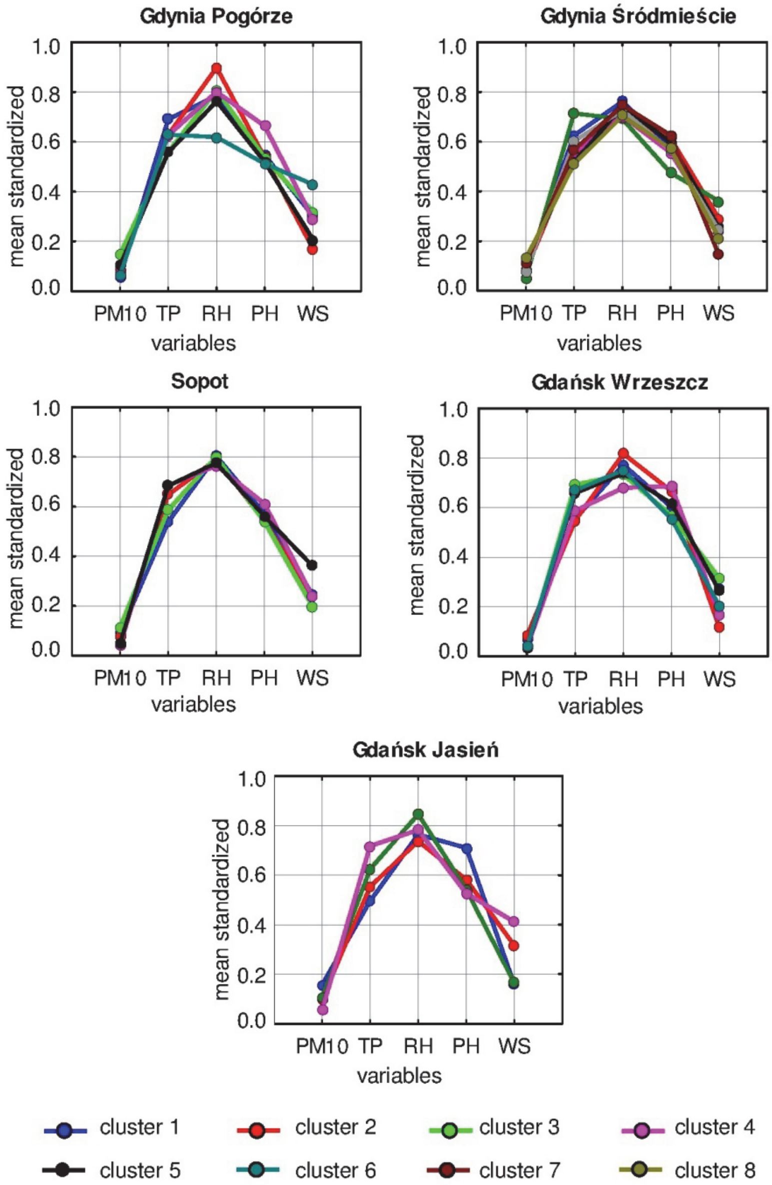

Fig. 4. Mean standardized values of particulate matter PM10 concentrations and meteorological elements for each recognized cluster
Rys. 4. Średnie standaryzowane wartości stężeń PM10 i elementów meteorologicznych dla wydzielonych skupień

Table 2. Characteristics of particulate matter (PM10) concentrations and meteorological factors in distinct clusters
Tabela 2. Charakterystyka stężeń pyłu zawieszonego PM10 i elementów meteorologicznych w wyróżnionych skupieniach

station	cluster	PM10 [μg·m^{-3}]	AT [°C]	RH [%]	PH [hPa]	WS [m·s^{-1}]	cases [%]
Gdynia Pogórze	1	19.8	4.1	85.9	1016.9	2.6	14.8
	2	27.8	2.1	93.2	1016.0	1.5	18.8
	3	48.3	-0.1	87.2	1015.9	2.8	18.3
	4	23.6	2.0	86.8	1027.3	2.5	23.1
	5	34.6	-0.2	84.3	1014.6	1.8	17.8
	6	22.4	2.2	74.8	1013.9	3.7	7.3
Gdynia Śródmieście	1	42.3	1.8	81.9	1015.6	2.7	23.3
	2	43.0	-0.7	77.7	1018.5	3.0	6.2
	3	27.4	4.6	76.7	1007.2	3.7	11.2
	4	57.5	-0.4	77.6	1013.8	2.5	15.0
	5	59.9	-1.6	80.5	1017.1	2.7	11.7
	6	39.9	1.1	79.3	1014.6	2.6	8.1
	7	57.6	-0.1	80.8	1019.4	1.6	8.8
	8	67.6	-1.8	77.6	1015.1	2.3	15.7
Sopot	1	34.1	-1.9	86.7	1011.2	1.9	10.9
	2	30.3	2.0	85.7	1008.9	1.8	18.2
	3	42.9	-0.2	86.4	1008.7	1.6	25.2
	4	16.0	3.4	84.0	1014.5	1.8	14.6
	5	19.5	3.3	84.8	1010.4	2.8	31.0

AT – air temperature; RH – relative humidity; PH – normalized pressure; WS – wind speed

Table 2. cont.
Tabela 2. cd.

station	cluster	PM10 [µg·m^{-3}]	AT [°C]	RH [%]	PH [hPa]	WS [m·s^{-1}]	cases [%]
Gdańsk Wrzeszcz	1	44.1	-1.2	86.0	1014.7	2.4	36.1
	2	50.6	-1.4	88.7	1019.8	1.1	7.1
	3	20.6	3.4	83.6	1012.2	2.8	19.7
	4	22.2	-0.1	80.4	1021.3	1.5	7.9
	5	22.1	2.3	83.9	1016.0	2.3	17.6
	6	24.5	2.7	84.7	1011.2	1.8	11.5
Gdańsk Jasień	1	43.1	-4.4	83.7	1026.4	1.9	21.4
	2	27.6	-2.3	82.1	1016.3	3.8	24.8
	3	29.9	0.2	88.7	1013.2	2.0	25.1
	4	15.6	3.4	84.9	1012.0	4.9	28.8

AT – air temperature; RH – relative humidity; PH – normalized pressure; WS – wind speed

The negative effect of winter weather conditions in high pressure systems was most prominent in Gdańsk Jasień. The greatest concentrations of particulate matter, approximately 43 µg·m^{-3}, were recorded at the lowest air temperature that is -4.4°C, the lowest wind speed of 1.9 m·s^{-1} and highest pressure – over 1026 hPa (cluster 1). In the conditions of high, positive temperature over 3°C with twice as high wind speed and significantly lower pressure, PM10 concentration was almost 2.5 times lower (cluster 4). Also in Gdańsk Wrzeszcz the highest concentration of particulate matter was connected with the lowest air temperature and the lowest wind speed accompanied by increased, yet not the highest, pressure (cluster 2). In the remaining districts of Tricity high concentrations were recorded either in connection with great decrease in air temperature (Gdynia Śródmieście – cluster 8) or with relatively low wind speed (Sopot – cluster 3), occurring both in conditions of elevated as well as decreased pressure. The results were inconsistent mainly regarding humidity accompanying low and high concentration of PM10. For example, in Gdynia Pogórze the highest concentration of particulate matter (cluster 3) occurred at relatively high relative humidity, approximately 87%, and was lower by almost a half at relative humidity approximately 75% (cluster 6.)

The results of the regression analysis indicate that winter meteorological conditions had a statistically significant influence on the variability of particular matter concentration – Tab. 3. The total coefficients of determination proved to be statistically significant, yet ranged widely from below 2 to about 36%, depending on the district and cluster. In general, the accuracy of correlation was determined by the concentration of particulate matter in individual clusters. For every district of Tricity the weakest influence of meteorological conditions on immission was found in clusters grouping the average lowest concentrations of particulate matter. The strongest influence of weather on variability of greatest average particulate matter concentrations was found in Gdynia Pogórze and in both districts of Gdańsk. In the most polluted district of Tricity, that is Gdynia Śródmieście, the extreme values of the coefficients of total determination were calculated for cluster 7 involving the elevated, yet not the highest, hourly PM10 concentrations. The least variable values of the total determination coefficient was calculated for Gdańsk Wrzeszcz despite the fact that individual clusters grouped (individual) different (prevailing) wind directions.

Meteorological conditions which explain the variability of PM10 concentrations usually included 3–4 elements (Tab. 3). However, the development of the variability of PM10 concentration – expressed as coefficients of partial determination (r^2), was mainly due to air temperature and the wind speed. The positive influence of the meteorological elements on developing variability of immission was reflected by negative directional coefficients. The fundamental role of thermal and anemometric conditions in providing explanation for the concentration and variability of pollutants was shown in numerous research [3, 13, 14, 24].

Strong correlation between air temperature and particulate matter concentration in winter season in Tricity was found mainly in clusters grouping instances of high, yet not always highest, PM10 concentration. For example in Gdynia Śródmieście, the greatest values of the partial determination coefficient (25%), which reflect the significance of thermal conditions, were calculated for cluster 7. In this cluster, the average PM10 concentrations occurring mainly at SW winds was by 10 $\mu g \cdot m^{-3}$ lower than the highest concentration recorded in the same district – occurring mainly at SE circulation and classified as cluster 8.

Table 3. Coefficients of total determination (R^2) and coefficients of partial determination (r^2). in %. for the relationships between particulate matter(PM10) concentrations and meteorological elements in distinct clusters
Tabela 3. Współczynniki determinacji zupełnej (R^2) oraz determinacji cząstkowej (r^2). w %. dla zależności stężeń pyłu zawieszonego PM10 od elementów meteorologicznych w wyróżnionych skupieniach

station	cluster	R^2	r^2 element of meteorology			
			AT	RH	PH	WS
Gdynia Pogórze	1	9.8	0.6	·	1.8	3.9
	2	8.4	0.6	1.1	·	7.1
	3	23.0	12.1	5.1	·	7.9
	4	7.8	3.2	·	2.6	6.0
	5	23.0	12.5	0.3	3.2	0.3
	6	14.6	·	·	4.9	11.7
Gdynia Śródmieście	1	25.9	12.3	·	1.0	3.0
	2	11.8	·	1.9	1.1	6.1
	3	6.4	1.0	1.6	2.9	·
	4	17.4	10.2	·	0.5	1.4
	5	14.1	5.6	0.5	0.6	11.3
	6	14.9	2.1	1.0	1.9	3.2
	7	36.3	25.0	1.7	3.0	10.3
	8	16.2	8.3	·	0.3	9.8
Sopot	1	18.0	1.3	·	0.5	16.5
	2	28.3	14.3	·	2.9	1.4
	3	14.1	8.6	0.2	0.1	2.8
	4	1.6	·	·	0.3	1.7
	5	15.8	8.4	0.1	0.7	3.0
Gdańsk Wrzeszcz	1	16.9	11.8	0.3	·	4.3
	2	23.6	18.2	·	·	10.8
	3	16.7	6.1	·	1.3	2.6
	4	22.9	10.0	6.1	1.1	4.2
	5	17.0	11.1	0.3	0.2	0.5
	6	19.9	8.5	·	0.3	4.6
Gdańsk Jasień	1	22.7	12.3	0.7	0.4	8.0
	2	15.1	6.5	0.4	·	9.3
	3	20.9	8.3	1.0	2.9	9.4
	4	4.4	1.3	0.9	·	2.9

· not significant at p ≤0,05; 0.2 – underlined value indicates a positive; AT – air temperature; RH – relative humidity; PH – normalized pressure; WS – wind speed

Wind which is the main pollution transport agent in the lower part of the atmosphere, not only contributes to the dispersion of pollution, but also to its inflow from other emission sources which in urban areas are mostly local sources. The results of wind direction analysis at which the average highest one-hour concentrations of PM10 were recorded, are presented in Fig. 5. In the greatest part of Tricity, that is in the northern and central part of the agglomeration, the risk of occurrence of the highest PM10 concentrations was connected with SE winds. In Gdańsk Wrzeszcz the increased concentrations of PM10 were recorded at E winds, whereas in Gdańsk Jasień at W winds.

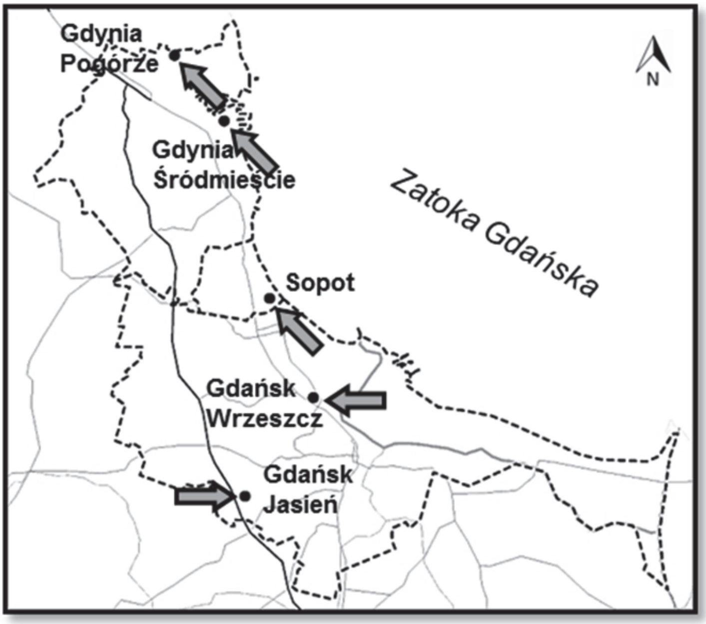

Fig. 5. Wind directions posing the greatest risk of high concentrations of particulate matter PM10 in Tricity urban area
Rys. 5. Kierunki wiatru stwarzające w okresie kalendarzowej zimy ryzyko wystąpienia w aglomeracji trójmiejskiej wysokich stężeń pyłu zawieszonego PM10

The influence of wind speed on the variability of PM10 concentrations proved to be smaller than that of air temperature (Tab.3). Only in two districts (Gdynia Pogórze and Gdańsk Wrzeszcz) the highest determination coefficients, thus the role of wind, were calculated for clusters grouping the highest PM10 concentrations. In other districts, the strong influence of wind was found in connection with much lower concentration of particulate matter. Wind served mostly as a ventilation factor in Tricity, and an increase in wind speed resulted in a decrease in particulate matter concentrations. The only case of negative effect of wind on particulate matter immission was found in Gdynia Pogórze, in cluster 6. Despite the fact that this cluster grouped concentrations recorded during meteorological conditions connected with NE circulation, that is the same as in the case of cluster 2, the increase in wind speed of this direction and also of SW and W winds was markedly correlated with an increase of particulate matter concentration. NE winds which were recorded more often in cluster 2, similarly to SW and W winds, contributed to the dispersion of particulate matter pollution. The complex and opposite role of winds of the same direction in the northern part of Tricity agglomeration can be attributed to the fact that it was found during different thermal and humidity conditions – positive at temperatures above 0°C (around 2°C) and high relative humidity but with low frequency of calms; and negative at temperatures below 0°C and low humidity (Tab. 2).

The comparison of data shown in Tab. 3 and 1 indicates that in Tricity agglomeration none of the predominant (in a cluster) wind direction was characterized by the strongest relationship between particulate matter concentrations and air temperature, not to mention wind speed. In every district the highest share of the elements mentioned above in the variability of PM10 particulate matter concentration was connected with different wind direction. Moreover, even within individual districts the greatest values of determination coefficients for both elements were calculated for different directions. Only in Gdańsk Wrzeszcz the strongest influence, both of temperature as well as wind speed, was found during prevailing winds of the same direction, namely E winds (cluster 2).

The share of relative humidity and atmospheric pressure in explaining the variability of particulate matter concentration proved to be incomparably lower, even statistically insignificant in some clusters, and ambiguous as for its direction. In most clusters, concentrations of PM10 showed a positive relationship with pressure, yet in some clusters the correlation was negative. The increase in relative humidity which is characteristic for cyclonic weather contributed both to an increase as well as decrease in particulate matter concentration in clusters including instances recorded at positive and negative air temperature. Therefore, the not so strong correlation between particulate matter and this element is not surprising. Relative humidity is not a coefficient which would characterize the concentration of water vapour in air well and definitely plays more important role in chemical changes of gaseous pollutants, mainly catalytic oxidation of sulfur dioxide. The correlation between immission of pollutants and relative humidity was demonstrated by Elminir [9], Freitas et al. [11], Pires et al. [27], yet with different directions depending on the type of pollutant, climatic conditions, season and local topography.

4. Conclusions

During the calendar winter (December - February), the northern part of Tricity which borders the waterfront areas and administratively belongs to Gdynia Śródmieście, is the most strongly PM10 polluted area of the urban agglomeration. Mean seasonal concentrations are by approximately 40% higher than in other districts and are marked by greatest variability.

The cluster analysis adopted in this study showed that average highest or increased hourly concentration of PM10 was recorded in Tricity on general during weather conditions of the lowest air temperature and smaller wind speed, as well as the greatest occurrence of atmospheric calms – that is in the conditions of anticyclonic weather. In much of the area of the agglomeration, in the districts Gdynia Pogórze and Śródmieście as well as in Sopot, the highest risk of high and excessive concentration of PM10 was connected with SE circulation. In the southern districts, the greatest risk was connected with E wind (Gdańsk Wrzeszcz) or W winds (Gdańsk Jasień), as is presented in Fig. 5.

Main meteorological elements affecting the variability of PM10 particulate matter concentration are air temperature, speed and direction of wind. The increase in air temperature and consequently lower emission, mostly connected with ineffective, scattered, local and individual heating systems, markedly contribute to the decrease in particulate matter concentration. Though directions of wind reflect inflow emission which originated locally as well as that coming from the outside of the agglomeration, in all districts of Tricity the increase in wind speed results in decrease of PM10 concentrations.

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Zastosowanie analizy skupień do wytypowania warunków meteorologicznych kształtujących zmienność stężeń pyłu zawieszonego PM10

Streszczenie

W pracy wykorzystano godzinne wyniki pomiarów stężeń pyłu zawieszonego PM10 oraz podstawowych elementów meteorologicznych rejestrowanych automatycznie w pięciu stacjach funkcjonujących w sieci pomiarowej Agencji Regionalnego Monitoringu Atmosfery Aglomeracji Gdańskiej (ARMAAG). Opracowaniem objęto okres kalendarzowej zimy (grudzień–luty) w latach 2004/2005–2009/2010. Zmienność stężeń zanieczyszczeń w warunkach pogodowych opisanych temperaturą i wilgotnością względną powietrza, ciśnieniem atmosferycznym oraz prędkością i kierunkiem wiatru, oceniono przy zastosowaniu analizy skupień, w tym metody k-średnich, z grupy metod niehierarchicznych. Kompleksowy wpływ warunków meteorologicznych na zmienność imisji pyłu PM10 w wyodrębnionych segmentach określono metodą liniowej regresji wielokrotnej, przy zastosowaniu procedury krokowej postępującej, na poziomie istotności $p \leq 0{,}05$. Udział poszczególnych elementów pogody w kształtowaniu wielkości stężeń określono za pomocą współczynników regresji cząstkowej. Zastosowany algorytm wyodrębnił, w zależności od dzielnicy Trójmiasta, od 4 do 8 optymalnych skupień najwięcej – w Gdyni, odznaczającej się największą imisją pyłu zawieszonego. W większości przypadków głównym czynnikiem zróżnicowania pomiędzy wyodrębnionymi skupieniami był kierunek wiatru. W przeważającej części aglomeracji trójmiejskiej, w Gdyni i w Sopocie, największą imisję pyłu zawieszonego PM10 notowano przy wiatrach SE, podczas gdy w części południowej, w Gdańsku, podwyższone stężenia pyłu notowano przy wiatrach E we Wrzeszczu oraz W w Jasieniu. Skupienia grupujące największe stężenie PM10 charakteryzowały się w większości przypadków najniższą temperaturą powietrza i mniejszą prędkością wiatru, a ponadto często wyższym ciśnieniem i niekiedy nieco mniejszą wilgotnością względną powietrza, czyli warunkami panującymi przy pogodzie antycyklonalnej. Warunki meteorologiczne miały statystycznie istotny wpływ na stężenia PM10 we wszystkich skupieniach, ale zasadniczą rolę odgrywały temperatura powietrza oraz prędkość wiatru. Wiatr, niezależnie od kierunku, był na ogół efektywnym czynnikiem wentylacji przyczyniając się przede wszystkim do zmniejszenia zapylenia powietrza.

Słowa kluczowe:
analiza skupień, regresja, PM_{10}, warunki meteorologiczne

Keywords:
cluster analysis, regression, PM_{10}, meteorological conditions