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Application of the Principal Component Analysis (PCA) Method to Assess the Impact of Meteorological Elements on Concentrations of Particulate Matter (PM_{10}): A Case Study of the Mountain Valley (the Sącz Basin, Poland)

Zbigniew Zuśka [1], Joanna Kopcińska [2], Ewa Dacewicz [3], Barbara Skowera [1,*], Jakub Wojkowski [1] and Agnieszka Ziernicka–Wojtaszek [1]

1 Department of Ecology, Climatology and Air Protection, Faculty of Environmental Engineering and Land Surveying, Hugo Kołłątaj University of Agriculture in Krakow, Al. Mickiewicza 24/28, 30-059 Kraków, Poland; rmzuska@cyf-kr.edu.pl (Z.Z.); rmwojkow@cyf-kr.edu.pl (J.W.); agnieszka.ziernicka-wojtaszek@urk.edu.pl (A.Z.-W.)

2 Department of Applied Mathematics, Faculty of Environmental Engineering and Land Surveying, Hugo Kołłątaj University of Agriculture in Krakow, ul. Balicka 253c, 30-198 Kraków, Poland; rmkopcin@cyf-kr.edu.pl

3 Department of Sanitary Engineering and Water Management, Hugo Kołłątaj University of Agriculture in Krakow, Faculty of Environmental Engineering and Land Surveying, Al. Mickiewicza 24/28, 30-059 Kraków, Poland; ewa.wasik@urk.edu.pl

* Correspondence: rmskower@cyf-kr.edu.pl

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Abstract: The aim of this study was to determine, by use PCA analysis, the impact of meteorological elements on the PM_{10} concentration on the example of the mountain valley. Daily values of selected meteorological elements, measured during a ten-year period in the spring, summer, autumn and winter, obtained from the meteorological station in Nowy Sącz, were adopted as variables explaining PM_{10} concentration. The level of PM_{10} was significantly affected by the maximum, minimum and average temperature in autumn, winter and spring. In summer the average and maximum temperature was significant. In winter, the first principle component mainly consisted of the combination of the average and maximum wind speed. The second principal component in spring, summer and autumn was the combination of the wind speed (average and maximum), but in winter humidity and atmospheric pressure seemed to be significant. The third principal component, in terms of strength of impact, was humidity in spring, the combination of humidity and minimum temperature in summer, and precipitation in autumn. In winter, the highest PM_{10} concentrations were observed during the non-directional, anticyclonic wedge conditions. Three principal components were distinguished in this situation: temperature (average, maximum and minimum); the combination of humidity and wind speed and precipitation.

Keywords: meteorological elements; PM_{10} concentrations; principal component analysis

1. Introduction

The problem of air pollution affects not only Poland, but Europe as a whole [1–3]. Particularly harmful to human health are fine particulates, among them PM_{10}, consisting of grains with diameters below 10 µm. Dust with such a small particle size easily penetrates the upper respiratory tract.

However, health effects can be much more serious if toxic substances are absorbed on the surface of dust particles [3–5].

Annual particulate concentrations monitored in urban and suburban areas significantly exceed the acceptable level [2,5,6]. The adverse effects of increased particulate concentrations on the environment have been discussed in numerous studies [7–11]. In the climatic conditions of Poland, the highest level of air pollution with suspended particulate matter is observed in the colder half of the year, particularly in winter [12–14]. Among the most polluted cities in Poland and in the world are those located in mountain valleys [1,15–17]. Research on the impact of meteorological conditions on particulate concentrations in the air has shown a clear relationship between elevated concentrations and specific weather conditions [18–22]. Researchers are increasingly investigating what factors, besides anthropogenic ones, are determinants of air pollution, such as elevated PM_{10} concentrations. The investigation of PM chemical composition is also of great concern in determining adverse health effects. In fact, numerous studies in the literature deal with a comprehensive PM characterization [23,24] and are often aimed at highlighting markers of specific sources such as biomass burning [25,26] and, in particular, from agricultural residues burning such as that mentioned by the authors (puddy-residue burning).

In this paper, we consider which meteorological elements significantly affect the level of air pollution and to what degree. Is it always the air temperature, and if so, is it the maximum, minimum or average temperature? Is the wind speed more important, or perhaps it is the atmospheric pressure? Hence, we need a method to answer these questions. One way to determine the dependence of particulate concentrations on the values of meteorological elements is to plot a multiple regression curve [6,18,22,27]. Unfortunately, this method does not yield reliable results for all data used. Data associated with meteorological elements are not independent, and when treated as explanatory factors, they result in an incorrect forecast of elevated particle concentrations. For this reason, we need a method to determine independent factors that indicate which variables significantly affect air pollution. Principal component analysis (PCA) is such a method. It has been used in many studies to isolate independent factors (principal components) that significantly explain the variation of a dependent variable [26,28–31]. The aim of this study was to determine which factors and by what degree PM_{10} concentrations increased in the air of the Sącz Basin in calendar seasons (spring, summer, autumn and winter).

2. Material and Methods

Daily values of meteorological elements recorded from 2006 to 2016 (ten-year period) at the Nowy Sącz station, belonging to the Institute of Meteorology and Water Management-National Research Institute were used in the study. They were temperature—average (T), minimum (Tm) and maximum (TM); total precipitation (PP); relative humidity (H); wind speed—average (V) and maximum (VM); and atmospheric pressure (Po50N20E—reduced to sea level) [32].

The average daily concentrations of particulate matter (PM_{10}), measured from December 2006 to November 2016 for 4 seasons (spring, summer, autumn, winter), were obtained from the air monitoring reference station in Nowy Sącz, belonging to the Regional Inspectorate for Environmental Protection in Krakow [33].

Nowy Sącz, the third most populous city in the Lesser Poland Voivodeship, is located in the centre of the flat bottom of the Sącz Basin. This mountain valley is about 300 km^2 (flat bottom occupies about 80 km^2) and is the fifth largest area in the Western Carpathians in Poland. The Sącz Basin is surrounded by the elevations of the Rożnów Foothills to the north, Sącz Beskid Mts to the south, the Low Beskid Mts to the east and the Wyspowy Beskid to the west. The bottom of the basin belongs to the Upper Vistula River Basin and was formed by the rivers Dunajec, Poprad and Kamienica Nawojowska (Figure 1) [34].

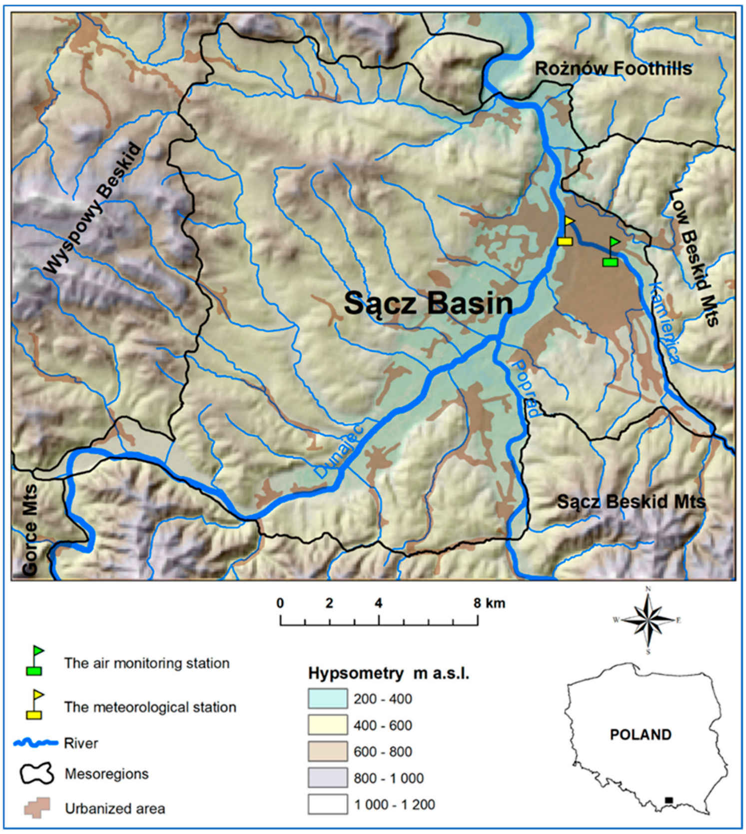

Figure 1. The area of the Sącz Basin and location of the air monitoring station and the hydrological and meteorological station in the Sącz Basin.

Figures 1 and 2 show the location of the hydrological and meteorological station of the Polish Institute of Meteorology and Water Management-National Research Institute and air monitoring station. As a part of the State Environmental Monitoring in Nowy Sącz, the Małopolska Voivodship Inspectorate for Environmental Protection operates one air monitoring station, which belongs to the national network. This station is certified by the Polish Institute of Meteorology and Water Management-National Research Institute, thanks to which its measurements are comparable with other stations in the nationwide network. The assumption of the location of this station was representativeness for a larger area with the same physiographic characteristics, and in this case for the basin.

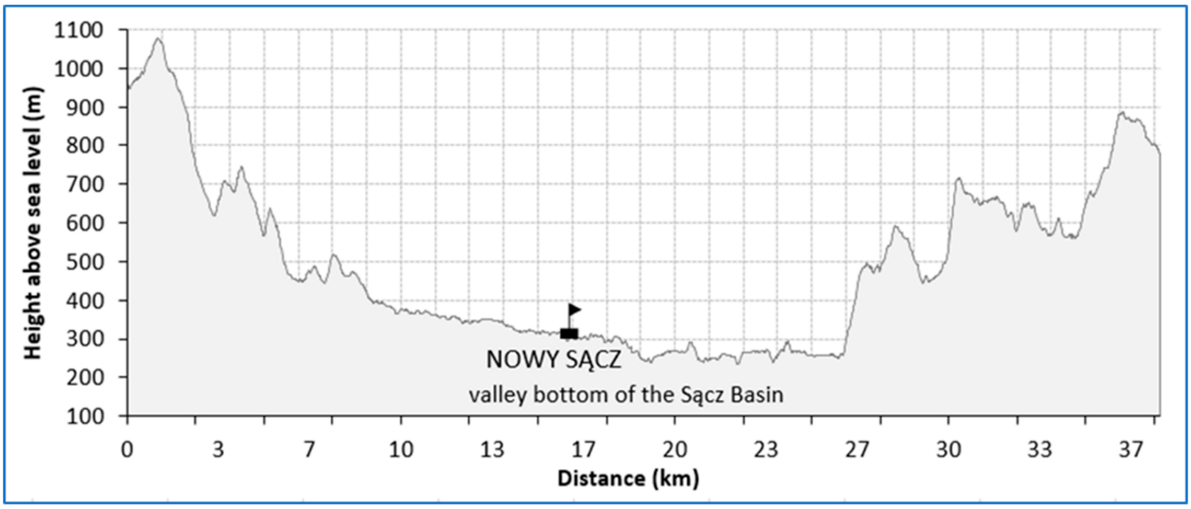

Figure 2. Location of the air monitoring station in the SE–NW profile of the Sącz Basin.

Principal component analysis (PCA) was used to analyze the dependence of particulate concentrations on meteorological elements. This method makes it possible to reduce the number of variables (usually dependent between themselves) affecting the particulate concentration and to determine which components, now independent, largely explain the variation of the PM_{10} concentration. Reducing the number of variables also simplifies the interpretation of the results [28,30,31,35,36]. In the PCA method, the variance is calculated in relation to all variables taken into account. In our case, the variables were the meteorological elements, such as: temperature—average (T), minimum (Tm) and maximum (TM); total precipitation (PP); relative humidity (H); wind speed—average (V) and maximum (VM); atmospheric pressure (Po50N20E) (treated as a part of independent principal components); and PM_{10} concentrations (dependent variable) taken for analysis. This method names new components by singling out the variables with the highest factor loadings in relation to the component data. The new principal components are therefore a linear combination of the explanatory variables (meteorological elements) that maximally affect this component, and thus the PM_{10} concentration (dependent variable). The number of principal components was determined according to the Kaiser criterion, which states that the eigenvalues of the correlation matrixare greater than 1 [37]. In each principal component, only those variables whose correlation coefficient (absolute values) were the highest were taken into account. The dependence of all variables on the principal components are presented on the plot, with each variable represented by a vector. The length and direction of the vector indicate the strength and direction of the variable's dependence on a given component. The location of the vector in a specific quadrant of the coordinate system indicates the positive or negative impact of this variable on a given component, and thus on the PM_{10} concentration. If the vectors are located close together on the graph, it means that these variables carry the same information about the variation in the system, and therefore it suffices to use any one of these variables for further analysis. An acute angle between the vectors of individual variables indicates a positive correlation between them, an obtuse angle means a negative relationship, and a right angle indicates no relationship between the variables. Calculations were performed using Statistica 13 (StatSoft Polska Sp. z o.o., Kraków, Poland, 2019).

3. Results and Discussion

The correlation matrix between variables and eigenvalues of the correlation matrix were calculated. The correlation coefficients between variables clearly showed that the explanatory variables (i.e., meteorological elements) were interdependent (Table 1). Therefore, determination of a regression equation could lead to incorrect predictions. For this reason, the PCA method was proposed, as it can be used to create linearly independent principal components which are a linear combination of meteorological elements.

Table 1. Correlation matrix of meteorological elements (2006–2016).

Spring	PM_{10}	T	TM (max)	Tm (min)	Po50N 20E	H	PP	V	VM
T	**−0.41**	1							
TM (max)	**−0.26**	**0.95**	1						
Tm (min)	**−0.55**	**0.87**	**0.70**	1					
Po50N20E	**0.37**	−0.18	−0.08	**−0.30**	1				
H	−0.13	**−0.28**	**−0.41**	0.07	−0.18	1			
PP	**−0.25**	−0.01	−0.09	0.14	−0.13	**0.32**	1		
V	**−0.27**	−0.14	**−0.23**	−0.03	**−0.29**	−0.15	0.11	1	
VM	**−0.22**	−0.05	−0.08	−0.01	**−0.25**	−0.19	0.07	**0.83**	1

Table 1. *Cont.*

Summer	**PM_{10}**	**T**	**TM (max)**	**Tm (min)**	**Po50N 20E**	**H**	**PP**	**V**	**VM**
T	**0.49**	1							
TM (max)	**0.51**	**0.93**	1						
Tm (min)	**0.24**	**0.69**	**0.48**	1					
Po50N20E	0.09	−0.03	0.01	−0.19	1				
H	**−0.23**	−0.46	**−0.54**	0.14	−0.16	1			
PP	**−0.25**	**−0.20**	**−0.26**	0.07	−0.15	**0.36**	1		
V	**−0.29**	−0.14	−0.19	−0.04	**−0.21**	−0.16	0.08	1	
VM	−0.18	−0.06	−0.07	0.00	−0.16	−0.12	−0.01	**0.73**	1
Autumn	**PM_{10}**	**T**	**TM (max)**	**Tm (min)**	**Po50N 20E**	**H**	**PP**	**V**	**VM**
T	**−0.38**	1							
TM (max)	**−0.24**	**0.93**	1						
Tm (min)	**−0.47**	**0.91**	**0.73**	1					
Po50N20E	**0.34**	−0.16	−0.07	**−0.21**	1				
H	**0.23**	**−0.35**	**−0.44**	−0.12	0.19	1			
PP	**−0.22**	−0.05	−0.15	0.08	−0.14	**0.26**	1		
V	**−0.44**	−0.03	−0.15	0.02	**−0.38**	**−0.41**	0.13	1	
VM	**−0.39**	0.02	−0.06	0.02	**−0.39**	**−0.46**	0.08	**0.88**	1
Winter	**PM_{10}**	**T**	**TM (max)**	**Tm (min)**	**Po50N 20E**	**H**	**PP**	**V**	**VM**
T	**−0.54**	1							
TM (max)	**−0.39**	**0.94**	1						
Tm (min)	**−0.59**	**0.94**	**0.80**	1					
Po50N20E	**0.29**	**−0.38**	**−0.35**	**−0.34**	1				
H	**0.28**	**−0.28**	**−0.37**	−0.13	0.08	1			
PP	−0.11	0.01	−0.01	0.06	−0.07	0.09	1		
V	**−0.57**	**0.38**	**0.32**	**0.36**	**−0.22**	**−0.54**	0.01	1	
VM	**−0.51**	**0.39**	**0.36**	**0.34**	**−0.23**	**−0.55**	0.00	**0.90**	1

In bold, the highlighted data represent values of significant correlation coefficient ($\alpha = 0.05$).

The correlation between meteorological elements and the PM_{10} concentration in the calendar seasons, i.e., spring, summer, autumn and winter, is shown in Table 2. According to the scale proposed by Stanisz [29] ($|r| > 0.5$), the strongest effect of the average and minimum temperature and of average and maximum wind speed on PM_{10} levels was observed during the winter. The influence of minimum and maximum temperatures was noted in the spring and summer, respectively. In autumn, the impact of all analyzed meteorological elements was significant but weaker ($|r| < 0.5$).

Table 2. Eigenvalues of the correlation matrix (2006–2016).

	Spring			**Summer**		
	PC1	**PC2**	**PC3**	**PC1**	**PC2**	**PC3**
Eigenvalue	2.81	2.02	1.60	2.73	1.86	1.58
% variance	35	25	20	34	23	20
% cumulative variance	35	60	80	34	57	77
	Autumn			**Winter**		
Eigenvalue	2.93	2.35	1.30	3.75	1.59	1.06
% variance	37	29	16	41	29	14
% cumulative variance	37	66	82	41	70	84

In the analysis of principal factor components, the percentage of total variance of one variable (PM_{10}), explained by the factor (PC) is the square of the factor load. It could be interpreted as the determination coefficient. Analysis of the eigenvalues of the correlation matrix (Table 2) revealed that three main principal components, which could explain about 80% of the total variance of the level of the dependent variable (PM_{10}). In each season, the percentage of total variance was slightly different. It was 80% of the variance of PM_{10} concentrations in spring, 77% in summer, 82% in autumn and 84% in winter.

Analysis of the principal components in each season reveals certain differences. In spring, PC1, which was a linear combination of the average maximum and minimum temperature (Table 3), had the greatest impact on the particulate concentration, explaining 35% of the total variance (Table 2). The second principal component (PC2) was the combination of the average and maximum wind speed, explaining 25% of the total variance. The third principal component (PC3) was mainly relative humidity, which explained 20% of the variance of the PM_{10} concentration (Table 2).

Table 3. The principal components of the meteorological elements (2006–2016).

Meteorological Elements	Spring			Summer		
	PC1	PC2	PC3	PC1	PC2	PC3
T	**−0.99**	0.08	0.01	**−0.96**	−0.13	−0.20
TM (max)	**−0.96**	−0.03	0.17	**−0.95**	−0.08	−0.03
Tm (min)	**−0.86**	0.22	−0.32	−0.57	−0.19	**−0.70**
H	0.29	−0.06	**−0.84**	0.57	0.25	**−0.63**
V	0.23	**0.89**	0.23	0.25	**−0.88**	0.15
PP	0.04	0.28	−0.62	0.38	−0.03	−0.57
VM	0.14	**0.88**	0.30	0.16	**−0.88**	0.16
Po50N20E	0.13	−0.56	0.49	−0.18	0.44	0.56
	Autumn			Winter		
T	**−0.95**	−0.28	0.09	**−0.88**	−0.40	0.22
TM (max)	**−0.89**	−0.35	−0.09	**−0.87**	−0.22	0.25
Tm (min)	**−0.85**	−0.23	0.33	**−0.77**	−0.51	0.22
H	0.56	−0.39	0.56	−0.12	**0.84**	0.44
V	0.08	**0.91**	−0.01	**−0.72**	−0.32	−0.52
PP	−0.21	0.18	**0.83**	−0.07	0.16	0.43
VM	−0.26	**0.90**	−0.07	−0.72	0.41	0.49
Po 50N20E	0.28	−0.53	−0.41	−0.31	**0.89**	0.24

In bold, the highlighted data represent correlation of variables when the absolute value > 0.7. Explanation of abbreviations: temperature—average (T), minimum (Tm) and maximum (TM); total precipitation (PP); relative humidity (H); wind speed—average (V) and maximum (VM); and atmospheric pressure (Po50N20E—reduced to sea level).

In summer, the most important principal component (PC1) was the combination of the average and maximum temperature (explaining 34% of the total variance of particulate concentration) (Table 3). The second principal component (PC2) was the combination of maximum and average wind speed (23% of the variance), and the third one was the combination of humidity and minimum temperature (20%) (Table 2).

In autumn, it was temperature (average, maximum and minimum) (Table 3) that had the greatest impact, accounting for 37% of the total variance of particulate concentration (Table 2). The second principal component (PC2) was the average and maximum wind speed, which explained 29% of the variance (Table 2). The third factor was precipitation, which explained only 16% of the variance of the data (Table 2).

In winter, the dependence of the PM_{10} concentration on selected meteorological elements differed slightly from the other seasons. The first principal component (PC1) was the linear combination of air temperature and wind speed, the second was humidity and atmospheric pressure, and there were no significant meteorological elements observed in the third principal component (Table 3). The three principal components explained 84% of the total variance, so it seems that the three factors should be taken into account. The first principal component (PC1) explained 41% of the variance and the second one (PC2) explained 29% (Table 2). However, the third principal component (PC3) explained only 14% of the variance in the PM_{10} concentration (Tables 2 and 3). Among the variables of the third factor, relative humidity seemed to affect the level of the concentration of PM_{10}. The combination of the wind speed (average and maximum) were placed in the first principal component (Table 3).

Analysis of the graphs (Figure 3) reveals different effects of meteorological elements (e.g., temperature and wind speed) on particulate concentrations. The location of the three temperature variables reflects their positive correlation. Perpendicular variables indicate a lack of correlation. This type of relationship was observed in spring, summer and autumn for variables describing temperature and wind speed. In autumn, i.e., in September, October and November, there is a drop in temperature and during this period the heating season begins. This explains an increase in air pollution emissions as a result of fuel combustion. As reported by Niedźwiedź and Olecki [38], in the autumn, in the southern part of Poland, the most common are the occurrence of high-pressure situations with advection from the west and without advection situation, i.e., the anticyclonic wedge situation. As demonstrated by Dacewicz et al. [15] and Palarz and Celiński-Mysław [17], especially in late autumn (November), high-pressure situations (Wa and Ka) occurred during this period for 25% of days in this season. Skowera and Wojkowski [39] showed that in these situations the lowest temperatures occurred in the area, and thus the consumption of fuels for heating increased. Combined with ever lower temperatures—and consequently the need for heating—this increases the emission of PM_{10} air pollutants. By analyzing episodes of high pressure over the Western Carpathians in January (the coldest month of the year), Palarz and Celiński-Mysław [17] noticed the same regularities in five valleys of the Polish Western Carpathians. They showed that high atmospheric pressure, and consequently the occurrence of thermal inversion and low negative temperatures, caused an increase in fuel consumption for heating.

The analyses were carried out without distinguishing types of weather, which significantly affect the dispersion of air pollutants [22,40,41]. The highest PM_{10} concentrations were noted during high-pressure, non-directional weather conditions, i.e., an anticyclonic wedge (Ka), which often shapes the weather throughout the year, especially in the winter [15–17,39,41]. Therefore, an analogous PCA analysis for this situation was also carried out (Table 4).

Table 4. Eigenvalues of the correlation matrix in anticyclonic wedge conditions (2006–2016).

Variable	PC1	PC2	PC3
Eigenvalue	3.07	2.08	1.62
% variance	38	26	15
% cumulative variance	38	64	79

The highest correlation coefficients obtained between the principal components and individual variables indicated that under the influence of anticyclonic wedge conditions, the PM_{10} concentration was 79% determined by three principal components.

The first principal component (PC1) was air temperature (38%) and the second one (PC2) was the linear combination of humidity and wind speed (26%). The third principal component (PC3) was influenced mainly by the atmospheric precipitation (15%) (Tables 4 and 5). The effect of precipitation was revealed only in one type of the synoptic situations in winter. The comparison of the graphs, showing the projection of meteorological elements on to the area of principal components PC1 and PC2, in any synoptic situation reveals that atmospheric pressure has a smaller effect on the particulate concentration than in the case of an anticyclonic wedge appearance in the winter (Figures 3 and 4).

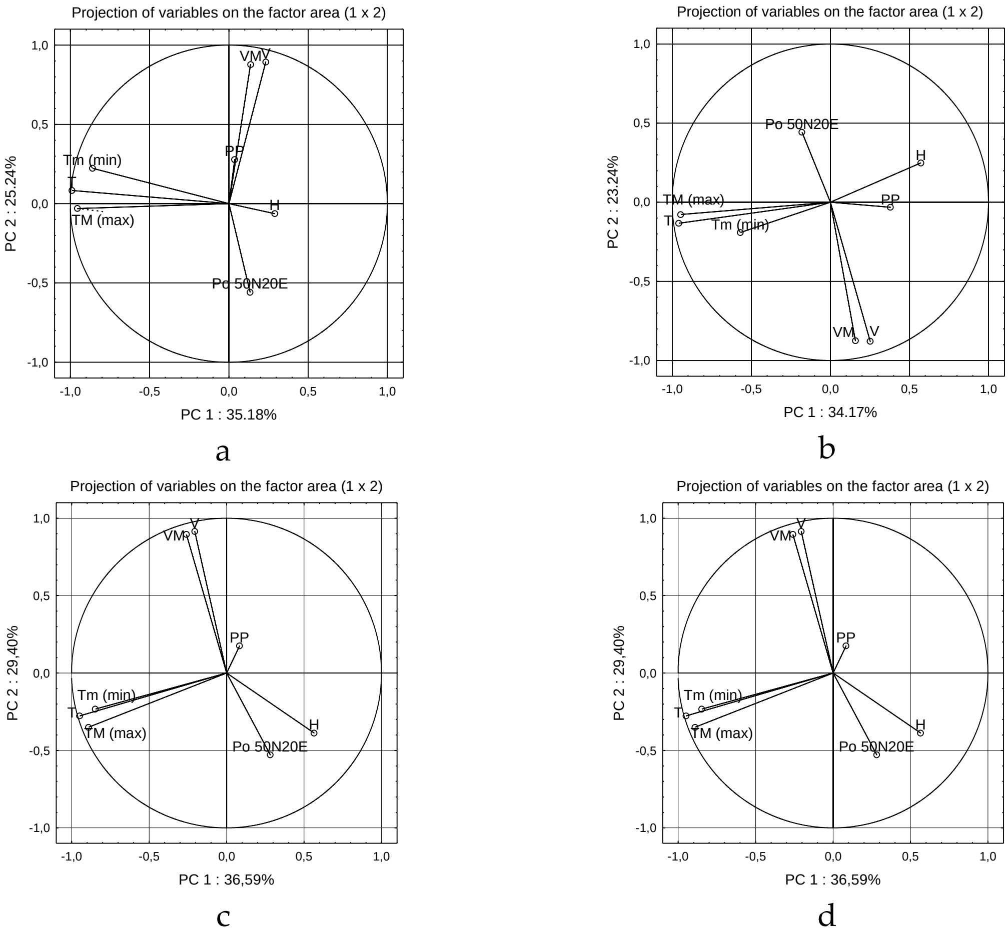

Figure 3. Projection of significant meteorological elements on the principal components area (1x2), PC1, PC2 in calendar seasons: spring (**a**), summer (**b**), autumn (**c**) and winter (**d**) (2006–2016).

Table 5. The principal components of the meteorological elements under the conditions of the anticyclonic wedge situation (Ka) (2006–2016).

Meteorological Elements	PC1	PC2	PC3
T	**−0.96**	0.21	0.16
TM (max)	**−0.90**	0.17	0.17
Tm (min)	**−0.91**	0.27	0.14
H	0.05	**0.78**	0.07
PP	−0.20	0.13	**−0.82**
V	−0.40	**−0.82**	−0.03
VM	−0.35	**−0.80**	0.04
Po 50N20E	0.43	−0.06	0.64

In bold, the highlighted data represent correlation of variables when the absolute value > 0.7. Explanation of abbreviations: temperature—average (T), minimum (Tm) and maximum (TM); total precipitation (PP); relative humidity (H); wind speed—average (V) and maximum (VM); and atmospheric pressure (Po50N20E—reduced to sea level).

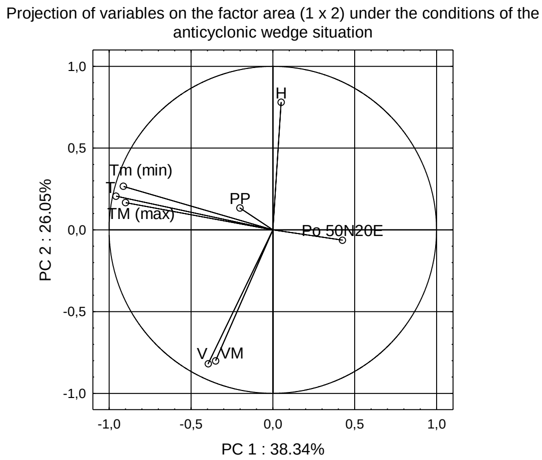

Figure 4. Projection of significant meteorological elements on the principal components area of PC1 and PC2 under the conditions of the anticyclonic wedge situation in the winter (Ka) (2006–2016).

The research has shown that application of the principal component analysis (PCA) method to assess the impact of meteorological elements on the PM_{10} concentration can be very helpful. The method PCA should be also tested for gas air pollution, for example, nitrogen and sulphur compounds [29].

4. Conclusions

The analysis of the impact of selected meteorological elements on the PM_{10} concentration in the Sącz Basin showed which of them seemed statistically significant.

In autumn, winter and spring, the effect of the maximum, minimum and average temperature was dominant (PC1), but in summer, only the average and maximum temperature seemed significant. In winter, an equally meaningful component was wind speed (average and maximum). The second component consisted of the combination of the wind speed (average and maximum) in spring, summer and autumn, and the combination of humidity and air pressure in winter. The third one, in terms of strength of impact, was mainly humidity in spring, humidity and minimum temperature in summer, and precipitation in autumn. In winter, precipitation seemed also significant, but only under the anticyclonic wedge conditions. Thanks to the PCA analyses, three main principal components seemed sufficient to explain most of the PM_{10} concentration levels in this meteorological situation. These were: the combination of average, maximum and minimum temperature (PC1); the combination of humidity and an average and maximum wind speed (PC2); and precipitation (PC3).

The PCA analysis of high PM_{10} concentration can be considered utilitarian. Recognizing the impact of meteorological elements on concentrations of atmospheric particulate matter can be useful in forecasting the occurrence of high PM_{10} levels in the mountain valley.

In the cool half-year, i.e., late autumn and winter, when the highest levels of PM_{10} occurred in Sącz Basin, the PCA analyses helped to show that the presence of high pressure systems and the accompanying low temperatures had the highest impact on pollution (conducive to emission and hindering dispersion).

The authors are planning further research, in which there will be taken into accountother factors as sources of PM_{10}, e.g., the amount of emissions and the origin of pollution in this area.

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