Impact of urban, suburban and industrial background on air pollution levels of dust substances in North-Eastern part of Krakow (Poland)

R Oleniacz, T Gorzelnik, M Bogacki
AGH University of Science and Technology, Faculty of Mining Surveying and Environmental Engineering, Department of Environmental Management and Protection, Krakow, Poland

E-mail: oleniacz@agh.edu.pl

Abstract. Air pollution in urban-industrial areas is caused by simultaneous impact of many factors, including different types of emission sources. Ambient air quality in Krakow is a crucial problem regarding the regularly occurring exceedances of limit values of particulate matter and some of its chemical compounds. This paper presents quantification of urban, suburban and industrial background of dust substances concentrations that are present in the industrialized area, located in the vicinity of scattered household and road traffic emission sources. There were included the concentrations of such substances as: particulate matter (PM$_{10}$), benzo(a)pyrene, arsenic, cadmium, lead and nickel. The impact of daytime and season of the year (especially heating and non-heating season) on variability of air pollutant concentrations was examined. In order to distinguish between local and inflow background of air pollutants the additional meteorological data concerning wind speed and direction was considered. The performed analyses included application of statistical methods, among others principal component analysis (PCA). Some of the results were visualized via R programming environment, providing tools for air pollution data processing (openair package). The backward trajectories modelling using HYSPLIT model, allowed the validation of wind direction analyses. The conducted research revealed the strong dependence of air pollution background type influencing the measurement results on instantaneous wind direction.

1. Introduction
One of the most essential issues in the scope of air quality management is the attempt of answer how much each types of emission sources contribute to the air pollution at a given point and what is the proportion of the same type of sources located at different distances or in different directions. The application of atmospheric dispersion models need to be preceded by detailed inventory of all emission sources, which have substantial influence on the air quality in a given area. The above is connected with the emission estimation, including the emission from diffuse sources (such as road transport, domestic heating, agriculture and small business), which is a difficult and time-consuming task and the estimates are to a large degree uncertain (as the final modeling results) [1-4].

Therefore, there have for many years been sought methods capable of more rapid identification of poor air quality causes. One of the possible directions of actions is application of receptor modeling. Receptor models are mostly based on measurements of meteorological parameters, concentrations of various air pollutants and chemical composition and/or physical properties of atmospheric aerosol, what typically requires conducting specifically designed measurement experiments [5-8]. There is also
a possibility for the use of measurement data obtained within the existing air quality monitoring networks, provided that the monitoring involves relevant substances and particulate matter components. Air quality assessment in Poland is conducted according to Directives 2008/50/EC [9] and 2004/107/EC [10]. In case of dust substances the assessment is usually performed based on direct air concentration measurements of particulate matter PM$_{10}$ as well as benzo(a)pyrene (BaP), arsenic (As), cadmium (Cd), lead (Pb) and nickel (Ni) in the PM$_{10}$ fraction. The content of another compounds in PM$_{10}$, including other polycyclic aromatic hydrocarbons and heavy metals, is not routinely monitored [11].

This paper is an example of assessment of urban, suburban and industrial background impact on dust air pollution level in selected part of the city of Krakow (Southern Poland), based on the application of this type of publicly available monitoring data. An analysis concerning the possibility of using only publicly available, fixed-site, pollutant and meteorological data in order to characterize the spatial and seasonal variability of PM$_{10}$ levels and to identify their main sources has been previously performed, among others, for such European cities as Athens, Birmingham, London and Madrid [12, 13]. In this work Principal Component Analysis (PCA) has been successfully applied. PCA is one of the most common techniques, which was implemented in receptor modeling, because it has the ability of reducing the original variables of a large dataset to a smaller number of uncorrelated principal components that explain a large fraction of the total variance [14]. There are known numerous applications of this method to identification of different groups of emission sources, including household sources, road transport or industrial facilities, such as e.g. steel works [15-24].

PCA and combination of various methods (considering e.g. backward trajectory models) have been recently applied for that purpose also for certain Polish cities (including Krakow), on the basis of specially planned measurements and results of air quality monitoring or biomonitoring [25-30]. In the studies [31-32] there have been presented the results of performed in recent few years analyses of PM$_{1}$ and PM$_{2.5}$ chemical composition in different periods during the year in the measuring point located in the vicinity of the city center of Krakow (district Krowodrza), where in the study [32] there have been presented results of positive matrix factorization (PMF) model as well. This analysis revealed that in winter, the combustion and secondary aerosols sources had a major contribution in PM$_{1}$ (90%) and PM$_{2.5}$ (81%) pollution. In the study [33] there have been demonstrated results of corresponding PM$_{2.5}$ sampling, carried out on urban background station in Southern part of Krakow. In the latter case, six sources were identified: secondary sulfate, secondary nitrate, combustion, biomass burning, steel industry/soil dust, and traffic. Additional information about elevated air pollutants concentration episodes are provided by analyses of pollution roses and backward trajectory modelling, performed for Krakow and presented e.g. in works [26-28, 34, 35].

The area analyzed in this study covers North-Eastern part of the city of Krakow, which is exposed to pollutant emissions from nearby industrial plants (i.a. iron and steel works, cement plant, combined heat and power plant, and municipal solid waste incineration plant) and, to some extent, from domestic furnaces and road transport. In recent years there were performed some actions, leading to reducing emission from these sources and their implementation improved partially the air quality in Krakow [36]. On the other hand there can be noticed the increasing impact of air pollution inflowing from beyond the city boundaries, what forced the need to expand the air quality management policy on adjacent municipalities. The dynamics of changes in particular emission sources activity, influencing air quality in this area is so large that the most rational solution is identification of effects of these changes basing on routine air quality monitoring results.

2. Materials and methods

In the conducted analyses there have been used the measurement results of air concentrations of selected dust pollutants (particulate matter PM$_{10}$ and As, Cd, Pb, Ni, and BaP contained in PM$_{10}$), available for the period of 2013-2018 or shorter, derived from three air quality monitoring (AQM) stations, located in North-Eastern part of Krakow (Figure 1): MpKrakBulwar (BU) – the industrial station operating since 1997, MpKrakOsPias (OP) – the urban background station operating since 2016 and MpKrakWadow (WA) – the industrial station operating since 2017 [37]. At these stations there are carried out continuous measurements (automatic measurements with time resolution of 1
hour, considered in the analysis) and periodic measurements (manual measurements averaged over 24 hours, not considered in the analysis) of PM$_{10}$ concentrations. Measurements of heavy metals and BaP concentrations are only periodic (manual measurements averaged over 7 days, considered in the analysis). In case of continuous measurements of PM$_{10}$ concentrations in examined period, there was applied one of following methods: β-ray attenuation (MetOne BAM-1020 dust monitor) or light-scattering (GRIMM EDM 180 dust monitor), considered as equivalent to the reference measuring method determined in [9]. Measurements of heavy metals and BaP, included in PM$_{10}$ fraction, were conducted in compliance with reference methods, resulting from respective EC directives [9, 10].

Identification and quantification of main type of particle emission sources has been carried out using Principal Component Analysis (PCA). PCA is a method of multidimensional analysis including decomposition of the input data set to data set consisting of principal components [8, 14, 38]. The principal components (PCs) are new variables, which are derived from original data set. The first PCs explain the majority of variance of the input data. Moreover, all of the principal components are orthogonal, what means that there is no linear correlation between the newly determined variables [38]. Principal components are interpreted as source profiles potentially affecting air quality at the receptor site. Factor analysis (FA) is similar to PCA and is also applied in receptor modeling, but they are two distinct techniques [6, 8]. The latent variables obtained by factor analysis are interpreted similarly to first principal components from PCA. In this study PCA has been performed for two air quality monitoring stations: MpKrakBulwar and MpKrakWadow. The air quality monitoring station MpKrakOsPias has been excluded from this analysis because of only BaP measured at this station. There have been considered five input variables in both cases (concentrations of As, Cd, Pb, Ni and BaP). As a result, two principal components have been extracted. In order to select principal components, it has been assumed that they must explain together at least 80% of variance. The analysis of obtained loadings allowed to attribute emission source classes to principal components. The PCA has been conducted in R programming environment (including psych package) [39-41].

In this work there has been also performed an analysis of time variability of PM$_{10}$ concentrations, recorded at particular air quality monitoring stations in the years 2013-2018, and the variability of average PM$_{10}$ concentrations in a given wind direction (between the stations) for the period in which the results of 1-hour concentration measurements for individual stations were available (2016-2018 or 2017-2018). In calculations of average concentrations there have been considered only the results corresponding to wind direction in a given (initial) hour, determined by a vector linking the analyzed pair of stations with tolerance ±10 degrees. In case of a station located on the opposite side from the
direction of the wind there has been considered the result in the same hour or with 1- or 2-hour latency, depending on wind speed and distance between particular stations. Additionally, there have been calculated average PM$_{10}$ concentrations at particular stations in the period of 2016-2018 or 2017-2018 for wind rose sectors corresponding to dominant background types (Figure 2). These types stem from location of the AQM stations in relation to urban and suburban areas, as well as large industrial facilities, and also with respect to the results of existing works assessing the impact of these facilities on air quality [42-46]. The results of these calculations have been compared with pollution roses for PM$_{10}$, performed for the AQM stations, and also with results of backward trajectories for years 2017 and 2018. The backward trajectory analysis, conducted in this study, allowed the identification of potential regional or long-distance pollution inflow and also the validation of wind direction analyses on the basis of single air particle trajectory modeling through HYSPLIT model [47, 48]. There has been applied a trajectory gridded statistical method counting the number of unique trajectories crossing a particular grid square. This method is accessible in openair package via function trajLevel integrated with HYSPLIT model [49-51]. The 96-hour back trajectories for studied area were generated first and they served as input data for above-mentioned gridded method.

![Figure 2. Sectors of dominant types of background adopted for the analyzed AQM stations.](image)

3. Results

PM$_{10}$ concentrations in ambient air, recorded at the analyzed AQM stations, are characterized by similar diurnal and annual variability with maximal values observed at night and in the winter period (Figure 3). This is confirmed by the significant impact of meteorological factors changing in the daily and annual cycle on the level of concentration of this substance, demonstrated among others in [34, 35, 52, 53]. With regard to the considered heavy metals and BaP, contained in PM$_{10}$ fraction, the most clear (multiple) increase of their concentration in the air in winter half-year in relation to summer half-year occurs in the case of As and BaP (Table 1). This is associated with varied activity of sources using solid fuels for heating purposes during the year and poorer dispersion conditions.

![Figure 3. The impact of daytime and season on PM$_{10}$ air concentrations variability [$\mu$g·m$^{-3}$].](image)
Table 1. Average air concentrations of heavy metals and BaP in PM$_{10}$ fraction at the AQM stations in North-Eastern part of Krakow in the analyzed period [ng·m$^{-3}$].

| Perioda | MpKrakBulwar | MpKrakOsPias | MpKrakWadow |
|---------|--------------|--------------|-------------|
|         | As  | Cd  | Pb  | Ni  | BaP | As  | Cd  | Pb  | Ni  | BaP |
| Summer half-year$^b$ | 0.85 | 0.65 | 21.2 | 1.63 | 1.23 | 0.62 | 0.56 | 10.8 | 1.06 | 0.66 |
| Winter half-year$^b$ | 2.38 | 1.38 | 46.2 | 1.99 | 11.1 | 8.85 | 1.35 | 18.4 | 1.28 | 9.16 |
| Year (all data) | 1.59 | 1.00 | 33.1 | 1.80 | 5.98 | 4.69 | 0.93 | 14.3 | 1.16 | 4.62 |

$^a$ Years 2013-2018 in the case MpKrakBulwar station, years 2016-2018 in the case MpKrakOsPias station and years 2017-2018 in the case MpKrakWadow station.

$^b$ Summer half-year: months IV-IX, winter half-year: months X-XII and I-III.

As in the case of As and BaP, concentrations of Cd and Pb are also highly correlated (Figure 4). However, their annual variability in this area seems to be determined mostly by industrial emissions (mainly iron and steel works) and to a significantly lower extent by seasonally varied processes of solid fuels combustion (domestic sources and combined heat and power plant). In turn, the observed Ni concentrations are not correlated with other PM$_{10}$ compounds and they generally occur on relatively low level. This indicates that emission sources of Ni are considerably scattered (i.a. combustion of solid and liquid fuels, alloy steels production, surface treatment and coating processes, emission from vehicles, wind erosion of soils and other natural sources [5, 15, 19, 22, 54]).

Figure 4. Scatterplot matrix for the analyzed heavy metals and BaP in PM$_{10}$ fraction at the industrial AQM stations: a) MpKrakBulwar, b) MpKrakWadow [ng·m$^{-3}$] (As, BaP, Cd, Ni) or [µg·m$^{-3}$] (Pb).

Results of PCA performed for weekly averaged concentrations of BaP, As, Cd, Pb i Ni as input variables, recorded at the AQM stations: MpKrakBulwar (in the period of 2013-2018) and MpKrakWadow (in the period of 2017-2018) are presented in Table 2 and Figure 5. This analysis...
showed that percent of cumulative variance for principal components PC1 and PC2 for the stations MpKrakBulwar and MpKrakWadow is 82.3 and 81.3 %, respectively (Table 2). Therefore, PC1 and PC2 satisfactorily explain existing variability of analyzed data set and further components (PC3-PC5) are not taken into account. This is confirmed by the first two eigenvalues (more than 3 and more than 0.9, respectively).

Table 2. Component loadings, eigenvalues and cumulative variance derived from PCA for the analyzed AQM stations.

| AQM station | Parameters | Parameters | PC1 | PC2 | PC3 | PC4 | PC5 |
|-------------|------------|------------|-----|-----|-----|-----|-----|
| MpKrakBulwar| Loadings   | As         | 0.882 | 0.254 | -0.277 | -0.284 |
|             |            | Cd         | 0.793 | -0.559 | 0.154 | 0.185 |
|             |            | Pb         | 0.874 | -0.432 | -0.205 |
|             |            | Ni         | 0.562 | 0.515 | 0.647 |
|             |            | BaP        | 0.807 | 0.381 | -0.379 | 0.242 |
|             | Eigenvalues|            | 3.138 | 0.975 | 0.668 | 0.141 | 0.077 |
|             | Cumulative var. |            | 0.628 | 0.823 | 0.956 | 0.985 | 1.000 |
| MpKrakWadow | Loadings   | As         | 0.887 | -0.426 | 0.132 |
|             |            | Cd         | 0.857 | -0.164 | 0.363 | 0.291 | 0.151 |
|             |            | Pb         | 0.933 | -0.164 | 0.185 | -0.255 |
|             |            | Ni         | 0.363 | 0.925 | 0.114 |
|             |            | BaP        | 0.790 | -0.567 | 0.232 |
|             | Eigenvalues|            | 3.146 | 0.918 | 0.508 | 0.323 | 0.106 |
|             | Cumulative var. |            | 0.629 | 0.813 | 0.914 | 0.979 | 1.000 |

Figure 5. Biplots presenting scores of each observation and loadings of each variable on PC1 and PC2 principal components for the AQM stations: a) MpKrakBulwar and b) MpKrakWadow.

Component loadings of input variables obtained for each analyzed principal component give an overview of degree of correlation between particular input variables and PCs. In case of the MpKrakBulwar station PC1 correlates moderately with Ni (loading: 0.562) and very strongly with BaP, As, Cd and Pb (loadings in a range of: 0.793-0.882). PC2 is related to mentioned variables with a low degree for BaP and As (loadings in a range of: 0.254-0.381) and with a moderate degree for Cd, Pb and Ni (loadings in a range of: 0.432-0.559). For the MpKrakWadow station component PC1 correlates weakly with Ni (loading: 0.363) and very strongly with BaP, As, Cd and Pb (loadings in a range of: 0.790-0.993), while component PC2 correlates weakly with Cd and Pb (loading: 0.164), moderately with Cd and Pb (loadings in a range of: 0.426-0.567) and very strongly with Ni (loading: 0.925).
Graphical interpretation of relationship between examined input variables and principal components PC1 and PC2 (Figure 5) allows to recognize homogenous groups of observations, whereas the principal components represent dominant type of emission sources affecting the stations. For the MpKrakBulwar station PC1 describes inflow of particulate matter pollution from the area of Krakow (urban background, originating mainly from household and traffic emission) and also from local industrial sources (industrial background) along the main wind directions (west, southwest and northeast). PC2 describes inflow of pollution from other directions. For the MpKrakWadow station principal component PC1 explains cumulative inflow of particulate matter pollution primarily from the area of Krakow and from industrial area (simultaneous impact of urban and industrial background), what occurs by southwest wind. The second principal component (PC2) explains inflow of pollution from other directions.

On both AQM stations the component loadings for each input variable (except Ni) are on similar level. Loadings for Ni in case of the MpKrakBulwar station are significantly lower than the corresponding values for the MpKrakWadow station.

In case of the MpKrakBulwar station there are observed two homogenous groups of input variables (the first group – BaP, Ni and As, the second group – Pb and Cd), which are weakly correlated with those in other groups and strongly correlated to each other. High correlation between Pb and Cd can be explained by inflows of air masses representing industrial background, involving mainly emissions from steel industry [5, 15, 19, 21, 26, 42]. This inflow occurs by northeast and east wind (approx. 20-30 % time of the year) (Figure 6). The impact of air emissions from the combined heat and power plant (southwest wind) and the municipal waste incineration plant (southeast wind) is relatively low, considering their distance and emission levels [43-46].

Strong correlation between BaP, As and Ni at the MpKrakBulwar station can be explained by the inflow of the air mass from the city of Krakow (urban background). The character of pollutants representing this group reflects mostly emission from burning fuels in domestic furnaces and energetic boilers, but also in combustion engines [17, 18, 24, 26]. The mentioned inflow is present by southwest and west wind. Large number of observations located in the center of Figure 5a (points close to each other) indicates the similarity of analyzed cases. This cluster of observations can evidence that the measurements were performed in similar conditions, for example during calms. Observations located at a greater Euclidean distance from the center of graph extend along two specific lines, which are almost orthogonal. This indicates the negligible correlation between the occurrences represented by these points. They correspond to the inflows at the MpKrakBulwar station from two opposite directions (urban and industrial background).

In case of the MpKrakWadow station there can be observed completely different relations of vectors representing input variables (Figure 5b). This is a result of location of the station in relation to dominant emission sources types, which are: the city of Krakow (urban background) and industrial area (mainly steel industry). These sources are situated in the west and southwest from this station (Figures 1 i 2). There is noticeable a very strong correlation between BaP, As, Cd and Pb, which can contribute to PC1, representing pollution inflow from Krakow and industrial area, in a large degree. The principal component PC2 can be identified with inflows from other directions (loadings indicating moderate negative correlation for BaP, As and low for Cd, Pb). Variable for Ni is very weakly correlated with BaP, As, Cd and Pb (the angle between Ni vector and other vectors is close to 90°). This variable has a low component loading on PC1 (0.363) and very high on PC2 (0.925). Strong impact of Ni on the second principal component can be explained by the fact that there are situated many diffuse Ni emission sources in the vicinity of the MpKrakWadow station, commonly fugitive emission sources. Specific, bipolar distribution of observations confirms the fact of strong polarization of analyzed pollutant groups contributions at particular station, what depends on wind sector, from which the pollutants inflow. Greater dispersion of observations indicates far larger variability of information included in specific measurements, as compared to the MpKrakBulwar station.

Air pollution roses of PM$_{10}$ presented for individual stations in Figure 6 confirm that the MpKrakBulwar and MpKrakWadow industrial stations are slightly more exposed to increased PM$_{10}$ concentrations in the air during winds blowing from directions in which industrial plants are located. Due to the proximity of large industrial plants, the measurement results of PM$_{10}$ concentrations at
these stations are also particularly sensitive to the variability of the annual wind rose, a characteristic example of which is the years 2017-2018. The significant decrease in PM$_{10}$ concentrations at the MpKrakWadow station in 2018 compared to 2017 (Figure 3) was caused, e.g., by an increase in the frequency of winds from the north-east and east associated with the inflow of air masses from outside the city of Krakow. The MpKrakOsPias urban background station is not exposed to emissions from these plants due to its location and the prevailing wind directions.

Figure 6. Air pollution roses of PM$_{10}$ obtained for the analyzed AQM stations in the years 2017 and 2018

Table 3 presents the calculation results of changes in average PM$_{10}$ concentrations at the individual pair of the AQM stations for the time episodes in which pollution was transported between analyzed stations, taking into account the instantaneous wind speed (transport time). Analysis of these calculation results allows, among others, for an approximate assessment of the impact of the industrial and urban background associated with the air emission sources located in the area between particular measuring stations. The highest average concentration increase has been found for the MpKrakBulwar (BU) station and for the MpKrakOsPias (OP) station during winds blowing from the region of MpKrakWadow (WA) station location through the iron and steel mill or its immediate surroundings (industrial background penetration). During the transport of air pollutants from the city of Krakow towards the OP and WA stations located on its north-eastern outskirts through the BU station, a certain decrease in average PM$_{10}$ concentrations (by approx. 5%) in relation to the BU station is visible. This is due to both the high level of urban background of this substance and the phenomenon of dilution of air pollution plumes in the process of their dispersion (diffusion effect) exceeding the level of local (including industrial) background.

Table 3. Average PM$_{10}$ concentration changes between particular pairs of AQM stations calculated for selected wind directions (during the wind blew between these stations) in the analyzed period$^a$.

| Parameter                          | BU-OP        | OP-BU        | BU-WA        | WA-BU        | OP-WA        | WA-OP        |
|-----------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Mean concentration [µg·m$^{-3}$]  | 39.8         | 37.6         | 21.4         | 22.5         | 45.8         | 43.3         |
| Concentration change [%]          | -5.6         | 5.3          | -5.4         | 16.6         | -2.1         | 7.6          |
| Number of 1-hour measurements (n) | 437          | 268          | 1523         | 1103         | 2912         | 963          |

$^a$ Years 2016-2018 for the pairs: BU-OP and OP-BU, years 2017-2018 for the other pairs.
Table 4 presents the variability of average PM$_{10}$ concentrations in the air observed at particular AQM stations with winds blowing from individual sectors corresponding to the dominant background types (urban, suburban and industrial) determined in accordance with Figure 2. This variability illustrates that the average level of PM$_{10}$ suburban background associated with the inflow of pollutants from areas located northwest, north and northeast of Krakow in the last 2-3 years was about 34 µg·m$^{-3}$, in the winter half-year approx. 45 µg·m$^{-3}$, and in the summer half-year approx. 22 µg·m$^{-3}$ (averages for the MpKrakOsPias and MpKrakWadow stations). The highest levels of urban and industrial background were obtained respectively for the MpKrakBulwar station (urban background of about 44 µg·m$^{-3}$) and the MpKrakWadow station (industrial background of about 47 µg·m$^{-3}$), while at the MpKrakWadow station the levels of urban and suburban backgrounds were very similar in the analyzed period (about 34 µg·m$^{-3}$, which represents approx. 72% of industrial background).

| Period | MpKrakBulwar UB | MpKrakBulwar SB | MpKrakBulwar IB | MpKrakOsPias UB | MpKrakOsPias SB | MpKrakOsPias IB | MpKrakWadow UB | MpKrakWadow SB | MpKrakWadow IB |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Summer half-year | 28.2 | 20.3 | 28.1 | 24.6 | 22.5 | 26.7 | 21.7 | 21.5 | 25.5 |
| n | 7118 | 133 | 4806 | 7118 | 1165 | 2259 | 4601 | 1397 |
| Winter half-year | 59.0 | 34.8 | 54.9 | 51.6 | 43.8 | 57.4 | 44.6 | 46.6 | 68.8 |
| n | 7934 | 194 | 5597 | 7038 | 4534 | 957 | 2393 | 4525 | 1358 |
| Year (all data) | 44.4 | 28.9 | 42.5 | 38.0 | 33.5 | 40.6 | 33.5 | 33.9 | 46.9 |
| n | 15123 | 327 | 10403 | 14156 | 8723 | 2122 | 4652 | 9126 |

| Period | MpKrakBulwar UB/SB | MpKrakBulwar IB/SB | MpKrakBulwar IB/UB | MpKrakOsPias UB/SB | MpKrakOsPias IB/SB | MpKrakOsPias IB/UB | MpKrakWadow UB/SB | MpKrakWadow IB/SB | MpKrakWadow IB/UB |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Summer half-year | 1.39 | 1.38 | 0.99 | 1.09 | 1.19 | 1.09 | 1.01 | 1.19 | 1.18 |
| n | 14156 | 8723 | 2122 | 4652 | 9126 |
| Winter half-year | 1.70 | 1.58 | 0.93 | 1.18 | 1.31 | 1.11 | 0.96 | 1.48 | 1.54 |
| n | 8723 | 2122 | 4652 | 9126 |
| Year (all data) | 1.54 | 1.47 | 0.96 | 1.13 | 1.21 | 1.07 | 0.99 | 1.38 | 1.40 |
| n | 14156 | 8723 | 2122 | 4652 | 9126 |

This work has shown a significant impact of the inflow background (identified with suburban background and the inflow of air pollution from greater distances) on the state of PM$_{10}$ air pollution in the North-Eastern part of the city of Krakow. As it results from Figure 7, presenting the results of modeling 96-hour back-trajectories for this region in the years 2017 and 2018, the occurrence frequency of these trajectories passing through individual sectors may fluctuate significantly year to year. Since the variability of the annual wind rose for the city of Krakow (Figure 6) and the seasonal PM$_{10}$ concentrations in the air (Figure 3) is observed in the same period as well, the final impact of long-range inflow background should be identified not based on the local wind rose but on the results of back-trajectory modeling. For example, in the year 2018 compared to 2017, the dominance of trajectories reaching Krakow directly from the west decreased and the frequency of trajectories from individual sectors changed significantly as well.

4. Conclusions

Time series of concentrations of the considered dust substances in the air indicate that a considerable seasonal variability of concentrations occurs only in the case of PM$_{10}$, As and BaP, which is associated with the varying activity of solid fuel combustion sources during the year. Cd and Pb concentrations...
are strongly correlated, and their variability is determined primarily by emissions from industrial sources (mainly iron and steel works). The observed Ni concentrations are not correlated with the concentrations of other PM$_{10}$ dust components and generally occur at a relatively low level, which indicates a significant dispersion of its emission sources (combustion, road traffic, metallurgy).

Figure 7. Occurrence frequency of 96-hour back-trajectories calculated for North-Eastern part of Krakow for the years: a) 2017, b) 2018.

PCA analysis carried out for two AQM industrial stations (MpKrakBulwar, MpKrakWadow) confirmed the close relationship between the location of the station and the main types of emission sources, and the prevailing wind directions. In the case of the MpKrakWadow station the overlapping of the industrial background (responsible for the increase in Pb and Cd concentrations) and the urban background (responsible for the increase in As and BaP concentrations) is observed, which does not appear in the case of the MpKrakBulwar station.

The average annual and seasonal PM$_{10}$ concentrations determined in particular AQM stations for wind direction sectors corresponding to the dominant background types (urban, suburban and industrial) allow an approximate identification of the role of individual types of background in shaping the state of PM$_{10}$ air pollution in the area of a given station location. The average suburban background of PM$_{10}$ specified for the stations located on the north-eastern outskirts of Krakow (MpKrakOsPias and MpKrakWadow) during their current operation was estimated at approx. 34 µg·m$^{-3}$, which indicates a significant level of PM$_{10}$ pollution of air inflowing into Krakow from northwest, north, north-east and eastern. The average annual (for the period 2017-2018) urban and industrial PM$_{10}$ background for the MpKrakBulwar station, located slightly closer to the city center, was obtained at about 44.4 and 42.5 µg·m$^{-3}$, respectively. The inflow of pollutants from industrial sources towards the MpKrakWadow station caused an increase in average PM$_{10}$ concentrations in relation to the suburban and urban background at this station by approx. 38-40 %.
Analysis of PM$_{10}$ air pollution roses showed a significant impact of the dominant wind directions in a given year on PM$_{10}$ concentrations recorded in the analyzed AQM stations (this justifies the differences in concentrations occurring in different years in some rose sectors). The origin of air pollutants associated with the inflow background should not be identified with the local wind direction, as this origin can be spatially and temporally variable, which is confirmed by the results of modeling backward trajectories. Further research in this area is recommended.

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