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AMBIENT AIR QUALITY FOR DIFFERENT WEATHER CONDITIONS IN TWO SITES OF OBSERVATION

JAKOŚĆ POWIETRZA DLA ODMIENNYCH WARUNKÓW POGODOWYCH W DWÓCH MIEJSCACH OBSERWACJI

Abstract: This paper presents the results of a short-term study into the variability of air quality corresponding to a variety of weather conditions in two observation spots differing in terms of urban development and land use character. The project reported here was conducted in the areas of housing development in the rural and urban areas during the cold season. The analysis involved 384 independent, 60-minute registrations of core air pollutants (NO_2, SO_2, O_3 and PM10). The research applied reference methodologies applied for measurements of physical parameters. The results of the registrations were compared by application of the Common Air Quality Index (CAQI) and the results were verified and analyzed by non-parametric tests (Spearman correlation and Wilcoxon ranked pair test). Consequently, it was stated that the comparison of air quality parameters by the application of the CAQI index provides an adequate solution. It was also observed that the short-term variability of the air quality parameters in the measurement spots is strictly related with the weather conditions in a given location. It was also concluded that during the cold season, the degree of urban development of the residential areas does not have a decisive effect on the course of the profiles of the core pollutants registered during one day. As a result, it was indicated that PM10 forms the source of pollution and determines the overall air quality. The study also revealed that air quality in the inhabited rural areas does not differ much from the more populated residential area in the town.

Keywords: winter, city, village, air quality, core pollutants, NO_2, SO_2, O_3, PM10

Introduction

The works containing reports into short- and long-term air quality in the vicinity of human dwellings provide a wide range of information regarding the sources of pollution, transformation of pollutants and their impact on human health [1–3]. A common direction of such study involves the determination of the impact of urban development on the local variations of the climate and aerosanitary conditions [4]. The

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processes occurring during chemical transformations and harmful impact of the primary pollutions are some of the topics that have been treated in depth and hence are well researched [5]. For a few decades, the parameters of air quality are expressed in relation to the admissible levels of the mass concentrations of core pollutants, including nitrogen dioxide, sulphur dioxide, ozone and particulate matter. In the urban domestic area, the principal sources of these pollutants include fossil fuel combustion from both stationary sources, *ie* power generation and mobile sources, *ie* transport. Tropospheric ozone (O_3) is a secondary pollution produced mainly by complex photochemical reactions occurring in the polluted air, for example with nitrogen oxides (NO_x) [6].

Apart from the determinants resulting from the manner in which useful energy is generated, the level of imission is affected by the weather conditions and characteristics of a given climate [7–9]. In the Central and Eastern Europe (in the moderate and subpolar climate) the greatest levels of pollutants are observed during the cold season, in particular on artic and windless days [10]. Another aspect is associated with the fact that the air quality and structure of emission sources (*eg* in Poland) is distinct from the ones that are recorded in the towns in Western Europe [11]. This pertains to both urban and rural areas. For instance in European rural areas most of PM comes from long-distant pollutant transport and natural sources. Its concentration is generally lower than in city centers and rarely causes any air quality problems [12–14]. In Poland, these conditions are completely distinct, which leads to a great deal of research focusing on the air quality in the winter months [10, 15, 16].

One of the ways to present the result is to apply air quality indices. Such indices are usually applied with the purpose of comparing aerosanitary conditions in towns. However, they can be successfully applied to verify the air quality in the rural areas, as well as in remote locations [17]. At present, studies offer an extensive use of the CAQI index [18], which describes the short- and long-term differences in the aerosanitary conditions in the locations selected for comparative purposes.

The objective of this work is to report on the results of study involving a comparison of the air variability for a variety of weather conditions in two observation sites with distinct characteristics in terms of urban development and land use character. This comparison applied Common Air Quality Index (CAQI) and statistical analysis. The result of the study took the form of the statements whose aim was to verify the following research hypotheses: – *during winter, for various aerosanitary conditions, the hourly variations in the air quality in a given location do not demonstrate statistically significant differences over the 24-hour period* (1), – *during winter, for identical weather conditions the degree of urban development do not affect the profile of the variability of the one-hour values of the parameters characterizing ambient air quality* (2).

Materials and methods

Measured pollutants, measurement sites and monitoring period

The study into the variability of the basic air quality parameters was undertaken in two sites. The observation spots were distinct in terms of the degree of urban development and domestic heating systems use character. The measurements values of the concentrations of core air pollutants (SO_2, NO_2, O_3 and PM10) performed concurrently over 1-hour periods were accompanied by registrations of the remaining meteorological parameters (atmospheric pressure P, wind speed and direction W, temperature T, rainfall R, relative humidity RH), which were collected for both urban and rural areas. The registration in the rural area were realized in the centre of village Kotorz Maly (Poland, 50°43′50″ N; 18°02′36″ E; 1025 inhabitants). The measurement point was located in direct neighborhood of compact rural building development area and main country road. All households in the rural area comprise individual energy and hot water supply systems. The representative data regarding the concentrations of the gaseous pollutants for the urban area (provincial town of Opole, Poland, 50°40′36″ N; 17°57′01″ E, 122,000 inhabitants), were gained from the air monitoring system managed by the Voivodeship Inspectorate of Environmental Protection (WIOS) [19]. The monitoring station of WIOS is situated in the centre of the biggest housing estate area in Opole city. As it has a population of around 20,000 people (8510 households spread around 134 buildings), the areas under this study are surrounded by a ring road with a high traffic volume. In contrast, all flats in the area under measurement apply heat derived from a district heating system.

The measurements and registrations were performed over 2 weeks throughout the period from January 9th to 22nd, 2017. The relative location of the two measurement spots in the vicinity of one another does not imply statistically significant differences in terms of the parameters defining weather conditions in the urban and rural areas. The verification of the research hypotheses applied a range of days which varying in terms of the weather conditions, *ie* January 11th, 2017 (a) and January 20th, 2017 (b). The weather in the denoted as "a" were characterized by unstable weather; T = 1–11°C, changeable western wind (W = 3–11 m/s), low value of pressure (P = 984–992 hPa) and variable humidity (RH =72–87%). For the case of the conditions defined as "b", greater weather stability was observed, however, considerable differences were present in comparison to the weather parameters defined for the date "a" [T = (–8)–(13)°C; W = 0–1 m/s (N); P = 1028–1031 hPa; RH = 68–71%). In both cases, no instances of precipitation were recorded in the periods applied in this study.

The methodology of sampling and data analysis

The study applied data from automatic measurement equipment realizing reference methodologies with the purpose of measurement of the mass concentrations of the physical parameters. In all cases, registrations were performed on an hourly basis over the entire period of the day. During the observations conducted in the rural areas, the mass concentrations of O_3, SO_2 and NO_2 were measured and registered by application Aeroqual AQM 60 apparatus [20]. The data regarding the mass concentrations of the gaseous pollutants in the urban area applied an automatic measurement station managed by the Voivodeship Inspectorate of Environmental Protection [19]. The mean hourly concentrations of PM10 in both locations were determined on the basis of the measurements by means of DustTrak DRX 8533 optical dust meters [21]. The information regarding the remaining aerosanitary parameters was gathered by the use of a portable Davis® weather station.

The data that was gathered was subsequently processed for further analysis. The Shapiro-Wilk test of normality demonstrates that the values of the particular parameters in the registration sites are not characterized by normal distribution. The further analysis of the data from the measurements applied non-parametric tests. The data that was adapted for the purposes of the statistical analysis was rescaled in accordance with the algorithm (1), as a results of which the impact of the absolute value of a given variable was reduced and the value of the variables were maintained in the range {0;1}.

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

The correlations between the variables were measured by the Spearman test, whereas the research hypotheses were verified by the Wilcoxon signed-rank test. For all cases significance level of 0.05 was adopted.

Results and discussion

Figure 1 presents the collective results of the registered one-hour mass concentrations of the particular pollutants in the examined locations. For the conditions defined as a) and b), both in the rural and urban environment we could observe a small variability of the concentrations only for the case of SO_2. Greater variations in the level of the measured parameters were recorded for the unstable weather (a). Concurrently, with the exception of O_3 and NO_2, a two times greater value of the median for the remaining compounds was noted for the stable weather (b). The *ad oculos* observations revealed that in the rural areas, during the two days corresponding to the duration of the reported measurement, individual heat sources (and, hence, point sources of the emissions) were exploited to a similar degree. The above statement confirms that the depreciation of air

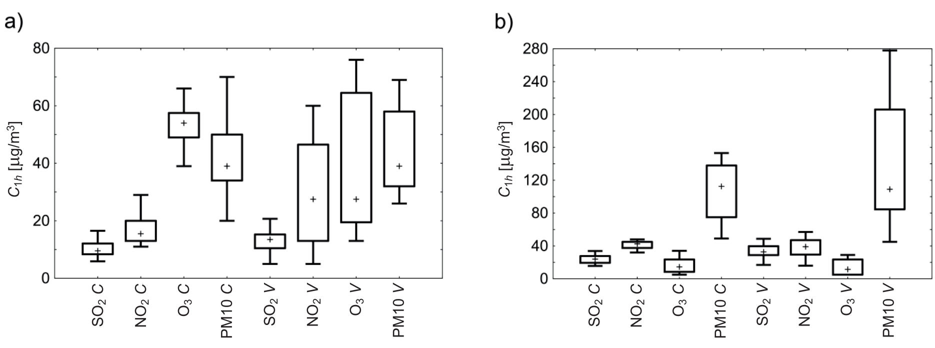

Fig. 1. Collective results of the registered one-hour mass concentrations, C_{1h} of the particular pollutants in the examined locations (*C* – city; *V* – village) for weather conditions a) and b). Boxes show the range between the 25th and 75th percentiles. The whiskers extend from the edge of the box to the 5th and 95th percentile of the data. The cross inside indicates the median value

quality is considerably correlated with the temperature drop, decrease of horizontal movement of air masses and increase and stabilization of the atmospheric pressure. The values of these parameters directly affect the effectiveness of the dispersion of pollutants in the troposphere. Concurrently, thermal conditions regulate the frequency and intensity of the use of the domestic heating systems. The position of the medians can indicate that with the exception for ozone, the greater values of the mass concentration of the examined core air pollutants were registered in the rural areas. This is probably due to the direct impact of the point emission sources in the vicinity. The mass concentration of PM10 is characterized by the greatest degree of variability in both measurement sites. Concurrently, only the concentration of the aerosol with the fraction below 10 micrometers exceeded the admissible levels (in the condition defined as (b)).

Table 1 presents the mean frequency of the occurrence of the particular classes corresponding to the general index and the sub-indices for the measured core air pollutants. As we can note, for the condition defined as (a), the sub-indices responsible for the gaseous pollutants are contained in the first (very low) and the second (low) classes, which means that the registered air pollution was small. In the long-term, for the case of the rural area, despite the very low and low values of the indices for SO_2, NO_2 and O_3, we cannot conclude that the air quality is overall satisfactory. Throughout nearly 40% of the periods corresponding to hourly results of registrations, the pollution assumes the value at the average level. In accordance with the CAQI index, this means that the air quality in the two measurement sites can be considered as similar. The detailed analysis of the hourly variations in the pollutant levels demonstrates that the PM10 formed the dominant pollutant (as it corresponded to 87% and 94% of total pollutant levels in the urban and rural areas, respectively). In the measurement spot located in Opole, despite the heavy traffic on the nearby ring road and local roads in the residential district (forming potentially the principal source of NO_2 emission in the analyzed town part), nitrogen oxide did not form the principal pollutant in any of the analyzed periods. This can also mean that the measurement sites was located too far from the main traffic arteries and the NO_2 concentration was diluted because of the horizontal movement of air masses. This result seems to confirm the conclusion stated by the Voivodeship Inspectorate of Environmental Protection that the most direct problem in Opole is associated with the pollution caused by particulate matter and this condition is regardless of the weather. Ozone was the dominant pollutant in the town throughout the four noon hours. This is quite standard for the effect and times when photochemical changes occur following the increased emission of nitrogen oxides accompanying its direct exposition to sun. For the case of the rural area, PM10 was the dominant pollutant recorded over 22 hours during the day. During the remaining 2 hours, it was not possible to identify the dominant source of pollution.

For the weather described by condition defined as B, in the urban areas we can observe average and high class of pollution. Despite the adverse conditions, and lack of states described as unstable atmosphere, the condition of very high air pollution did not occur during the experiment. This is likely to be due to the lack of the direct emission sources in the direct vicinity of the monitoring station. At the same time, the occurrence

Table 1

Frequency [%] of the occurrence of the index and sub-index classes (hourly data)

Index class	City					Village				
	Overall index	SO_2	NO_2	O_3	PM10	Overall index	SO_2	NO_2	O_3	PM10
Weather conditions “a”										
0–25	0.10	1.00	1.00	0.88	0	0.03	1.00	0.75	0.71	0
26–50	0.65	0	0	0.12	0.75	0.60	0	0.25	0.29	0.62
51–75	0.25	0	0	0	0.25	0.37	0	0	0	0.38
7–100	0	0	0	0	0	0	0	0	0	0
> 100	0	0	0	0	0	0	0	0	0	0
Weather conditions “b”										
0–25	0.08	1.00	0.88	1.00	0	0.05	1.00	0.87	1.00	0
26–50	0.05	0	0.12	0	0.04	0.02	0	0.13	0	0
51–75	0.31	0	0	0	0.33	0.22	0	0	0	0.29
7–100	0.56	0	0	0	0.63	0.38	0	0	0	0.38
> 100	0	0	0	0	0	0.33	0	0	0	0.33

Air quality index classes indication: 0–25 very low; 26–50 low; 51–75 medium; 76–100 high; > 100 very high.

of temperature inversion accompanied by a concurrent limitation of the exchange of air masses over the urban area has led to adverse aerosanitary conditions even in the urban area with high-rise building development. In this case, the principal source of pollution was associated with the local traffic. Nevertheless, the dominant pollutants did not include other substances than particulate matter. The greater distance from the stationary sources of fuel combustion for useful energy production also most likely has led to the fact that lowest class of air quality in this area did not occur. Such circumstances could not be avoided in the rural area, where the air quality was very poor throughout one third of the duration of the experiment. Again, very low and low sub-indices of air quality with regard to gaseous pollutants did not influence the overall air quality. The overall CAQI index broken down to the classes was considerable distinct from the result that was obtained in the urban area. The analysis of hourly variations in the concentrations of the particular substances demonstrates that PM10 was the only dominant pollutant. The considerably more adverse situation in the area of the compact rural development was associated with the excessive aerosol concentrations particularly in the afternoon and evening hours. Such circumstances directly result from the effect of the meteorological condition and common application of obsolete facilities as sources of heat production for households. The differences could not be explained in terms of the differences in the climate conditions, as it is often explained during the comparison of the CAQI indices for various towns around Europe [18].

Table 2 presents the results of the Spearman correlation for the particular pollutants corresponding to the two sites and meteorological conditions.

Table 2

Spearman correlation. *Rho* values. Results with bold fonts are statistically significant with $p < 0.05$. Italic fonts indicate data for village

Parameter	SO_2	NO_2	O_3	PM10
Weather conditions "a"				
SO_2		**0.36**	–0.33	**0.41**
NO_2	***0.77***		–0.28	–0.03
O_3	*–0.38*	*–0.15*		**–0.38**
PM10	***0.80***	***0.58***	*–0.23*	
Weather conditions "b"				
SO_2		**0.44**	–0.25	**0.47**
NO_2	***0.55***		–0.17	0.24
O_3	*0.32*	*–0.22*		**–0.35**
PM10	***0.83***	***0.73***	*–0.22*	

For all analyzed pollutants, statistically valid relations were observed between the variables nearly in the same list. Only for the urban area, the correlation index took on significant values for the relation between O_3 and PM10. Nevertheless, in accordance with the Guillford scale, the relation that was established is weak. The lack of a considerable relation between the concentration of ozone and its main precursor (NO_2) results from the delay in the increase of ozone concentration originating from the physicochemical transformations of carbon monoxide. The considerable negative correlation between the ozone and PM10 is likely to be due to the different hours when the concentrations of the two compounds occur and it seems to be rather coincidental. The forecasted and very strong positive relation between particulate matter and sulphur dioxide occurred for both meteorological conditions in the rural area. This relation is also more visible in the rural than in the urban area, and it demonstrates the characteristic of significance as well. This result confirms the commentary to the results from Table 1 and expressly indicates that the heating systems in the rural areas use low quality fuel which are enriched with sulphur. The relation between the mass concentrations of NO_2 and SO_2 as well as NO_2 and PM10 in the two sites prove to be significant, and we can note that for the results in the rural area, we can note the impact of the point emission sources from domestic boilers. Besides, weather conditions (*ie* greater values of *rho* for the condition defined as "b") have an influence on the value of the correlation coefficient.

It is interesting to note the mutual relations between the same types of pollutants measured concurrently in the urban and rural area. Statistically relevant Spearman correlations were only established for the case of PM10 (–0.64 and –0.54, for the conditions defined as "a" and "b", respectively). At the same time, during the unstable weather (a), a considerable positive relation was established for the nitrogen dioxide concentrations. The normalized profiles developed in accordance with the formula (1) for hourly concentrations of the pollutants and the particular locations and conditions confirm the results of the correlations (Fig. 2).

As for the fluctuations in the mass concentration of NO_2 for the conditions defined as (a), we can observe the occurrence of two maximums. For the case of the urban area, this is predominantly attributable to the increased traffic (corresponding to the morning and afternoon rush hours). For the rural area, the reason is associated with the periods corresponding to the intensive use of the domestic boilers. The calculated correlation coefficient confirms the results of the graphical interpretation. For the urban area, during the stable weather conditions (b), the profile of the distribution of the hourly NO_2 concentrations does not bear resemblance to the profile in the rural area. In the latter case, we can only observe an afternoon-evening peak, and the morning increase in the concentrations is characterized by a further stabilization, which also corresponds with the meteorological conditions, however, it is not compatible with the further sudden increase. For the rural area, we can observe a similar profile to the one that was observed for the conditions in (a).

With regard to the profiles of the mass concentrations of ozone, in particular for the urban area, we can observe a delay in the occurrence of the lowest values of the concentrations in relation to the ozone precursor, namely NO_2. Regardless of the weather, the highest concentrations are recorded in both measurement sites around the noon. Particularly high concentrations in the town are noted after dusk (a), which can mean that the conditions in the troposphere tend to remain constant due to the lack of forces enabling the atmosphere to get rid or reduce the impact of the derivative

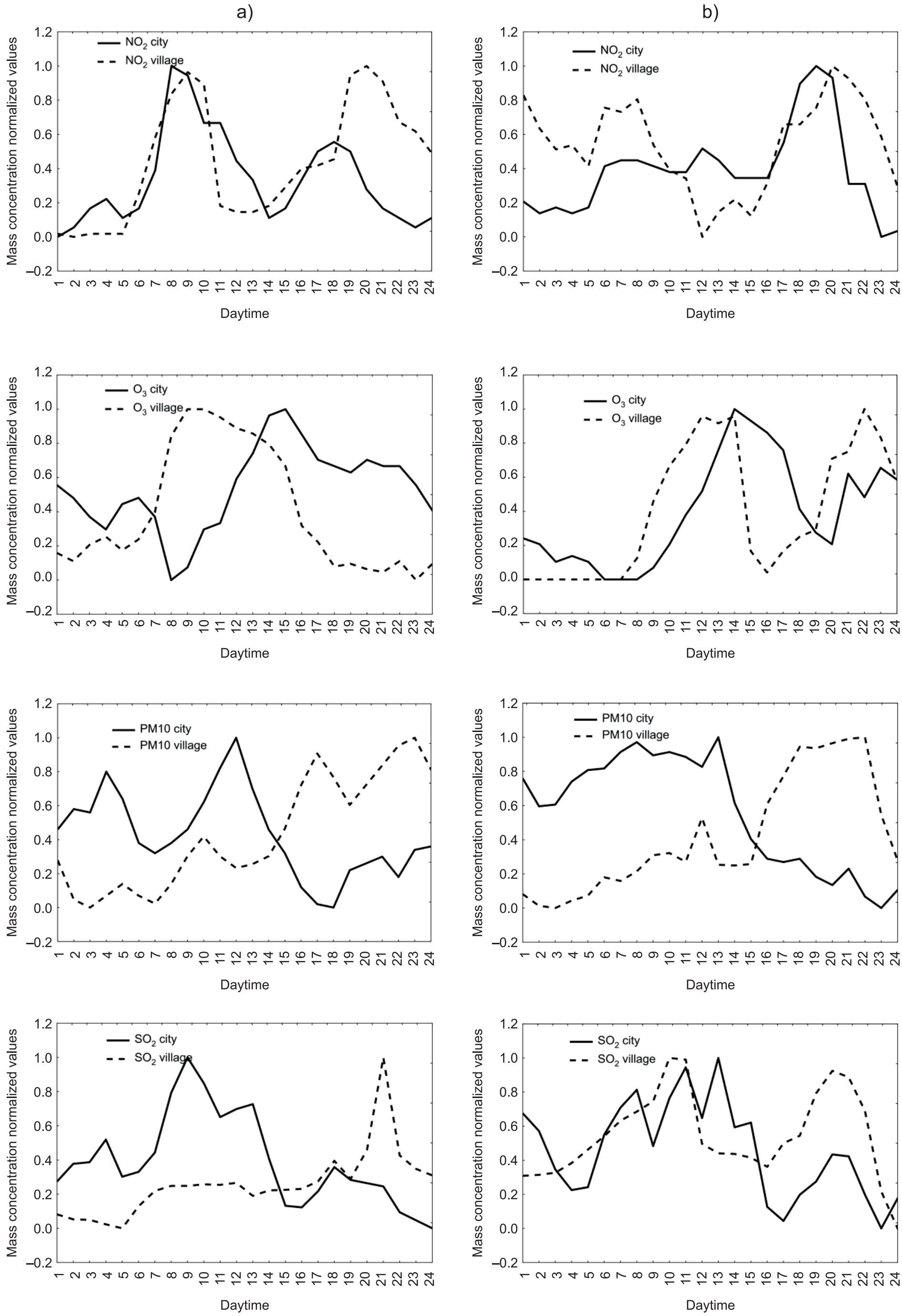

Fig 2. Core pollutants profiles for a) and b). Weather conditions (hourly data)

compounds. The evening and night increases in the ozone concentrations, which are followed by subsequent maximums in both areas for the condition defined as (b) are difficult to interpret, in particular in the context of the occurrence of the stable conditions in the ground level troposphere.

It is equally difficult to explain the profile of the hourly variations in the aerosol concentrations in the urban area accompanying the condition defined as (b). A sharp, evening drop in the concentration of PM10 in Opole was also confirmed the results of the air quality monitoring registered by another Voivodeship Inspectorate of Environmental Protection station located at the distance of 4 km from the one used in this study [19]. The above fact suggests that equipment error as well as non-specific short-term changes in the parameters of the ground troposphere are out of the question. In turn, adequate interpretation is made difficult.

The drop in the PM10 concentration in the town (during the condition defined as “a”) could be justified by the action of the wind and minimization of the impact of the emission sources in its close vicinity. Concurrently, the increase in the concentration of aerosol in the rural area was determined by the more intensive exploitation of domestic boilers resulting from the temperature drop in the evening, which is confirmed by the registrations made in the vicinity of the measuring equipment. The evident differences in the profiles of aerosol concentrations in both sites are revealed in the values of the Spearman correlation coefficient.

For the case of the profiles representing the variations in SO_2 concentrations, we can note differences between the rural and urban areas. For the case of the former, despite the statistically insignificant correlations, we can conclude that the hourly variations in the concentration of sulphur dioxide are similar to the profiles for PM10, which confirm the impact of the principal source which determines the air quality in the rural area. As for the town, we can observe considerable fluctuations, in particular at the times corresponding to the occurrence of the stable weather (b). The nominal values of the SO_2 concentrations are relatively small in comparison to the concentrations of the remaining pollutants (which is confirmed by the CAQI sub-index). This, in turn, can have an impact on the variations of the normalized values that were demonstrated by the profile.

The ultimate verification of the similarity of the mass concentrations of the core pollutants in the tested sites involved the verification of the research hypotheses stated at the beginning. Both hypotheses were verified by the application of the Wilcoxon’s signed-rank test. As a consequence, it was found that both in the urban and rural areas, the concentrations of the compared pairs of identical pollutants determined during diverse weather conditions were statistically different. In none of the cases, we could establish the exceeding of the level of the test relevance ($p < 0.001$). Hence, the hypothesis stating that *during winter accompanied by a variety of weather conditions, the hourly variations of the parameters characterizing air quality in a given area do not reveal statistically relevant fluctuations along the 24-hour period* has to be definitely rejected.

The Wilcoxon’s signed-rank test demonstrated that during the weather conditions described by the unstable conditions of the ground-level troposphere (A), the hourly mass concentrations of SO_2 and PM10 measured in the urban and rural areas did not reveal statistically significant differences (p = 0.051 and p = 0.484, respectively). However, statistically significant differences were registered for the case of NO_2 and O_3 ($p < 0.01$). During the weather conditions described by the stable ground-level troposphere (B), statistically significant results were established only for SO_2 ($p < 0.01$) with regard to one-hour mass concentrations. For the remaining pollutants, statistically significant results were not found ($p = 0.057$ for NO_2, $p = 0.654$ for O_3 and $p = 0.383$ for PM10). The result of this test indicated that the verified hypothesis that *during the winter, for identical weather conditions, the degree of urban development do not affect the variability profile of the on-hour values of the parameters characterizing the air quality* can be considered as true only to a limited extent.

Conclusions

The comparison of aerosanitary conditions in two and more locations performed by means of the CAQI index always forms a suitable solution. The results of a comparison of indices and sub-indices are similar to the classical approach conducted with the aim of verification, such as statistical analysis. The summary of CAQI data enables the researchers to study the potential changes in the ratios of the particular emission sources in a given area.

In the cold season, during the occurrence of the stable weather in the urban and rural areas, the levels of the pollutants in the immission phase are primarily affected by the local emission sources. We can assume that the results gained in the residential areas in towns and areas of compact rural development will be representative for a wide range of applications, primarily due to the similar pattern of useful energy consumption in the households (district heating in the urban and domestic boilers in the rural areas). The short-term variability of the aerosanitary air quality is strictly linked to the weather conditions, determined mainly by the pressure, temperature and direction and speed of air masses. The compared values registered during 24-hour profiles of the principal air pollutant indicate that the degree of urban development of the residential areas does not have a decisive impact on the characteristic and course of these profiles. For both observation spots it was observed that aerosol forms the dominant pollution determining the air quality in the examined areas.

The conditions of the air quality in winter, expressed by the one-hour tests, were found to be similar in the rural areas with compact development and in the vicinity of the greater and more populated residential district in the urban area (despite the fact that the latter is free of the individual sources of pollutant emissions associated with energy production from fuels). For the case of severe bad weather (in which dispersion of pollutants is limited and causing the more intensive use of the domestic boilers), the air quality in the rural areas was proved to be worse than in the nearby town. The similarity in terms of the characteristics of the use of individual heat sources in the households located in the rural areas in Poland leads to the statement that the above conclusion is true for a wider population.

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JAKOŚĆ POWIETRZA DLA ODMIENNYCH WARUNKÓW POGODOWYCH W DWÓCH MIEJSCACH OBSERWACJI

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Abstrakt: Artykuł przedstawia wyniki krótkoterminowych badań nad zmiennością jakości powietrza dla odmiennych warunków pogodowych w dwóch, różniących się stopniem zurbanizowania i sposobem użytkowania, miejscach obserwacji. Projekt badawczy przeprowadzono na obszarze osiedli mieszkalnych w mieście i na wsi w sezonie chłodnym. Przeanalizowano 384 niezależnych, 60-minutowych rejestracji wartości stężenia podstawowych zanieczyszczeń powietrza (NO_2, SO_2, O_3 i PM10). Wykorzystano referencyjne metodyki pomiarów wielkości fizycznych. Rezultaty rejestracji porównano przy wykorzystaniu ogólnego indeksu jakości powietrza (CAQI) a następnie przeanalizowano i zweryfikowano przy użyciu testów nieparametrycznych (korelacji Spearmana i testu Wilcoxona). Stwierdzono, że porównywanie jakościowych parametrów powietrza w różnych lokalizacjach przy użyciu CAQI jest dobrym rozwiązaniem. Wykazano, że krótkotrwała zmienność aerosanitarnej jakości powietrza jest ściśle związana z panującymi warunkami pogodowymi. Stwierdzono, że w sezonie zimowym, stopień zurbanizowania terenów zamieszkałych nie ma decydującego wpływu na dobowy kształt profili stężeń podstawowych zanieczyszczeń. Wykazano, że zanieczyszczeniem ustalającym ogólną jakość powietrza jest PM10. Znaleziono, że w okresie chłodnym, jakość powietrza na zamieszkałych obszarach wsi nie jest lepsza niż na znacznie bardziej ludnym osiedlu miejskim.

Słowa kluczowe: zima; miasto; wieś; jakość powietrza; zanieczyszczenia wskaźnikowe, NO_2, SO_2, O_3, PM10