Journal of Elementology ISSN 1644-2296

Czarnecka M., Nidzgorska-Lencewicz J., Rawicki K. 2016. *Thermal inversions and sulphure dioxide concentrations in some Polish cities in the winter season.* J. Elem., 21(4): 1001-1015. DOI: 10.5601/jelem.2016.21.1.1038

ORIGINAL PAPERS

THERMAL INVERSIONS AND SULPHUR DIOXIDE CONCENTRATIONS IN SOME POLISH CITIES IN THE WINTER SEASON

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Abstract

The influence of thermal inversions on the variability of sulphur dioxide concentrations in calendar winter (December to February) was assessed based on a 10-year measurement series from 2004/2005 to 2013/2014. The data on daily sulphur dioxide concentrations were obtained from four urban air quality measurement stations operated in a measurement network by the Regional Inspectorate of Environmental Protection (WIOŚ) in Wrocław, and from the ARMAAG Foundation in Gdańsk. The occurrence of thermal inversions was traced based on data from aerological measurements conducted twice daily (at 00:00 and 12.00 UTC) at two aerological stations, in Wrocław and in Łeba. This allowed for determine the thickness of the surface (lower) inversion layers, as well as the height of the base and thickness of the first (the lowest) layer in the free atmosphere (elevated). The effect of inversion on the variability of daily SO_2 concentrations was investigated using single linear regression at statistical significance levels of $\alpha = 0.05$ and $\alpha = 0.01$. The conditions of dispersion of the pollutants in the lower troposphere in the winter seasons from 2004/2005 to 2013/2014 were predominantly determined by the elevated inversion layers, which occurred in both regions at comparable frequency of almost 90%, both in daytime and nighttime. Surface inversions were recorded significantly less frequently, mostly at night. The data also showed that the thickness of inversion layers and the height at which they formed affected the concentration of SO_2, although the statistically significant role of elevated inversions manifested itself at both times of the 24-hour period, whereas the role of surface inversions was evident only at night.

Keywords: thermal inversions, concentration, SO_2, winter, regression.

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INTRODUCTION

Air pollution is one of the most important indicators of environmental quality, and its adverse effects on living organisms has been proven in many works (e.g Beard et al. 2012, Chwil et al. 2015).

In winter, the quality of air is dependent predominantly on excessive concentrations of particulate matter less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$), as well as benzo(a)pyrene (PMŚ 2014, Nidzgorska-Lencewicz, Czarnecka 2015). However, the concentration of SO_2 also has a significant effect on air quality. Similarly to particulate matter, the concentration of SO_2 recorded during the heating season is approximately 1.5- to 2-fold higher than that recorded in the summer season. In severe winter periods and unfavourable air dispersion conditions, SO_2 concentrations are even 3- to 5-fold higher than in summer. The main cause of air pollution in Poland is the burning of coal for heating, especially in households. The Polish coal monoculture does not have any equivalents in the EU (GUS, 2014). Approximately 70% of Polish households are heated with coal, often of poor quality, burnt mostly in obsolete furnaces. Energy combustion of fuels, mainly coal in furnaces, contributes approximately 75% of the national emissions of PM10 and almost 100% of the national emissions of sulpfur dioxide (IOŚ-PIB 2015).

Air quality depends on various factors. The most important are emissions and the weather conditions that determine dispersion of pollutants (Czarnecka, Nidzgorska-Lencewicz 2011, Majewski et al. 2011, Rawicki 2014, Rogalski et al. 2014, Żyromski et al. 2014, Czarnecka, Nidzgorska-Lencewicz 2015). Among the meteorological conditions affecting pollutant dispersion, thermal inversions are of significant importance. Temperature inversion is a natural phenomenon of a change in the normal tendency of air temperature with altitude. Temperature inversion means that temperature in the troposphere increases with altitude. Inversions, most often accompanied by a stable equilibrium in the atmosphere, impede vertical movements in the atmospheric boundary layer, simultaneously promoting higher concentrations of pollutants, which can reach values harmful to human health (Janhäll et al. 2006, Olofson et al. 2009, Beard et al. 2012, Gramsch et al. 2014). The results obtained by Wallace and Kanaroglou (2009) show an increase of 49% and 54% in NO_2 and PM2.5 respectively, during nighttime inversion episodes. According to Czarnecka and Nidzgorska-Lencewicz (2017), the unfavourable conditions of dispersion in the days with exceeded PM_{10} limit values in winter are mainly shaped by the thickness of surface inversions. The intensity of inversion is another significant factor. Katsoulis (1998) demonstrated a relationship between the intensity of inversion and SO_2 concentrations.

Due to the specificity of research conducted for the purpose of determining the occurrence of inversions, there have been a relatively limited number of publications on this issue. In Poland, aerological measurements are conducted only in three stations (Łeba, Legionowo and Wrocław), and patrol acoustic sounding is performed only by few research organisations.

As a continuation of the research on the effect of inversion layers on the concentration of main air pollutants, this paper focuses on the analysis of sulphur dioxide concentration. The influence of thermal inversions on the variability of SO_2 concentrations in calendar winter was analyzed with single linear regression.

MATERIAL AND METHODS

The input data consisted of mean daily concentrations of sulphur dioxide recorded in the winter (December – February) of 2004/2005 to 2013/2014, obtained from four air quality monitoring stations in the Tricity and in Wrocław. The Tricity agglomeration was represented by stations at Leczkowa Street in Gdańsk-Wrzeszcz and at Porębskiego Street in the northern part of Gdynia-Pogórze. The results were obtained from automatic measurement stations operating by the Agency of Regional Air Quality Monitoring in the Gdańsk metropolitan area (ARMAAG) (*http://armaag.gda.pl/)*. The stations located in Wrocław belong to the network of the Regional Inspectorate of Environmental Protection (WIOŚ). One station is located at Wybrzeże J. Conrada-Korzeniowskiego in Wrocław-Karłowice and the other is at Wiśniowa Street in Wrocław-Krzyki. Both stations in the Tricity area and the station in Wrocław-Karłowice are classified as urban background stations. The measuring station in Wrocław-Krzyki is the only communication station.

The occurrence of temperature inversions was investigated with the use of daily results of aerological measurements taken at 00.00 UTC and 12.00 UTC and provided by the aerological stations in Łeba and in Wrocław. On the grounds of aerological sounding, the thickness of surface-based (lower) inversion layers and the altitude of the base together with the thickness of the inversion layer in the free atmosphere (elevated) were determined. The above characteristics of inversion were developed separately for nighttime (00.00 UTC) and daytime (12.00 UTC). The inversion thickness, in both lower and elevated layers, was determined by the layer in which an increase in temperature coincided with an increase in altitude, that is with the vertical temperature gradient. Regarding surface inversion, the layer extended directly from the ground level to an altitude where the air temperature followed normal distribution that decreased with altitude. Frequently, there are several elevated inversions in the thermal structure of troposphere, particularly over the urban and industrial areas, separated with layers at which the temperature decreases with altitude. This paper focuses only on the elevated inversion layers closest to the ground level, i.e. the lowest elevated inversions. The influence of an inversion on the variability of daily concentrations of sulphur dioxide was evaluated with single linear regression analysis. The results of the calculations, at the significance levels of $\alpha = 0.05$ and $\alpha = 0.01$, were presented using determination coefficients R^2 in %. Since the distribution of the two correlated variables, and especially the characteristics of in-

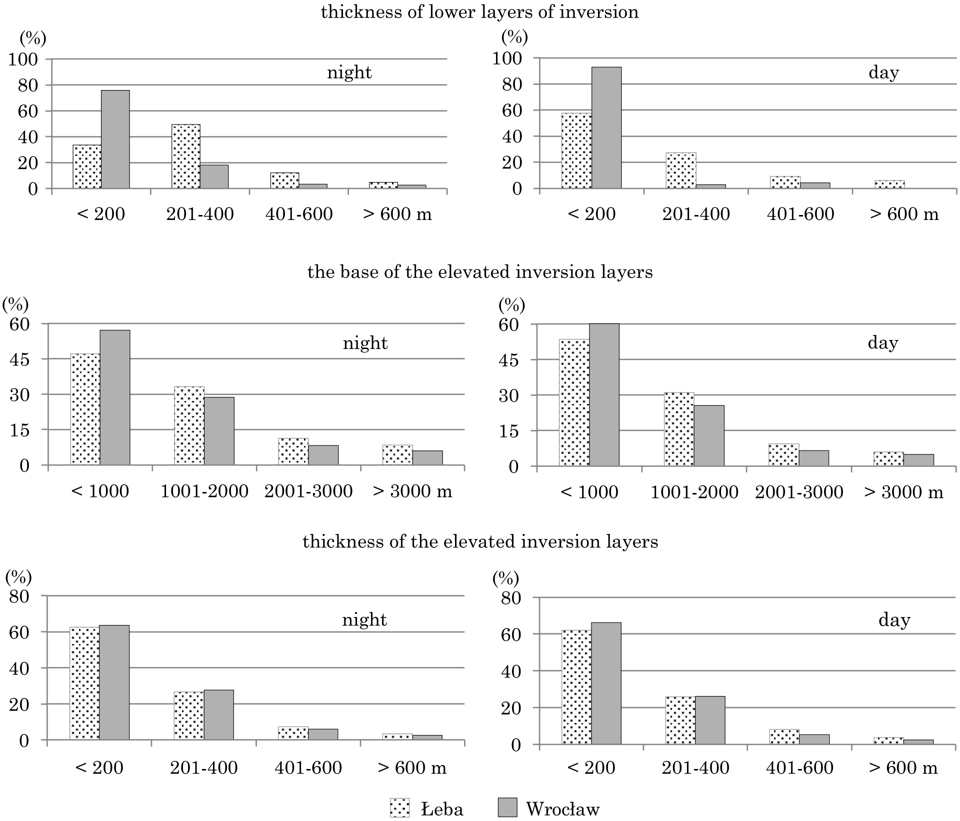

Fig. 1. Characteristics of the thermal inversions. Years 2004/05-2013/14

version layers, is different from the normal one (Figure 1), which was confirmed by the Kolmogorov-Smirnov & Lilliefors test for normality, regression analysis was conducted using the Box-Cox transformed data. The Box–Cox technique was chosen among numerous methods for series transformation to

$$y^{(\lambda)} = \begin{cases} \dfrac{x^{\lambda} - 1}{\lambda}, & (\lambda \neq 0) \\ \ln x & (\lambda = 0) \end{cases}$$

a distribution approximate to consistent with the normal distribution, where: $y^{(\lambda)}$ – transformed variable, λ – the main parameter of transformation.

In order to apply the Box-Cox transformation, the value of parameter must be established (BARTCZAK et al. 2014), which requires the iterative method. In Statistica 12 software, which was used for calculations, parameter in the Box-Cox transformation is established by the Golden search.

RESULTS AND DISCUSSION

According to the Environmental Protection Inspectorate (GIOŚ) report, the average annual concentration of SO_2 in the agglomeration of Wrocław was significantly higher than in the Tricity. This was also confirmed by the results pertaining to the calendar winter (Figure 2). In the analyzed 10-year

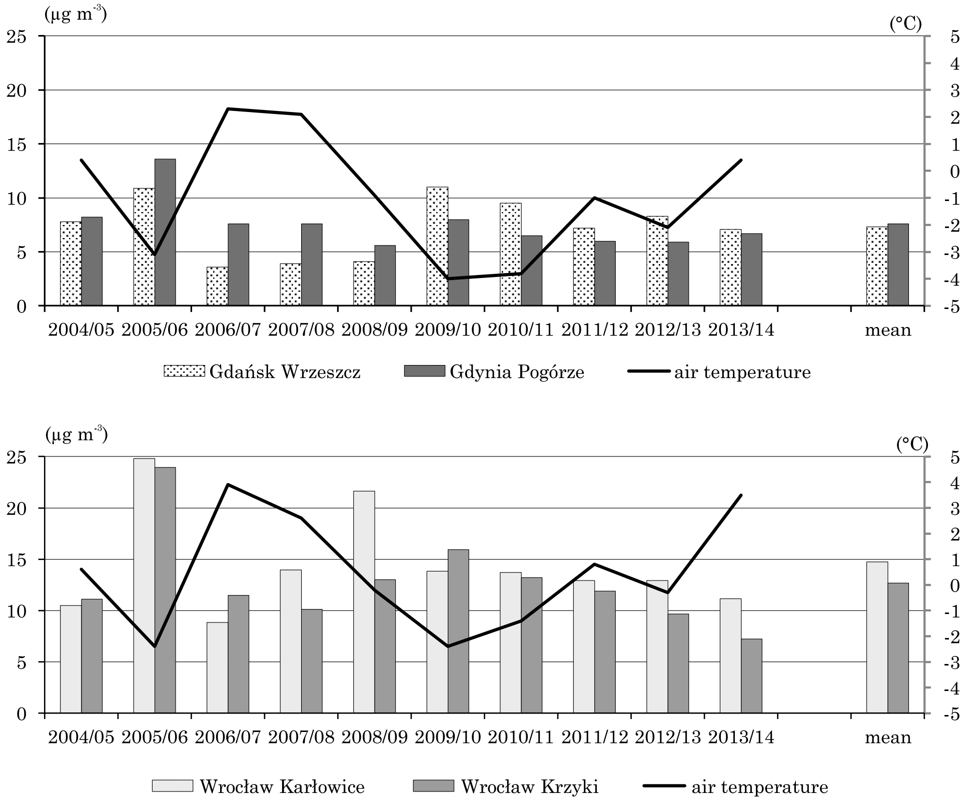

Fig. 2. Average seasonal (December - February) SO_2 concentration in the background of air temperature. Years 2004/05 - 2013/14

period, the mean seasonal concentration of sulphur dioxide recorded in Wrocław was twice as high as in the Tricity, not only in the seasons characterized by increased concentrations. In both cities, the highest concentrations of sulphur dioxide were recorded in the freezing winter season of 2005/2006. In Wrocław, the mean concentration recorded then was almost 25 µg m^{-3}, whereas in Tricity it did not exceed 14 µg m^{-3}. In Gdańsk-Wrzeszcz, a high concentration of SO_2 was additionally recorded in the winter season of 2009/2010, which according to the Institute of Meteorology and Water Management (*www.imgw.pl/extcont/biuletyn_monitoringu/*) could be classified as very cold. In Wrocław-Karłowice, very high concentrations were recorded in the winter of 2008/2009, characterized as average in terms of thermal conditions. In that winter season, the differences in sulphur dioxide concentrations between both districts of Wrocław were most conspicuous, which implicates other sources of emission, apart from heating, as well as the meteorological conditions affecting the SO_2 concentration. Since the main source of pollution with SO_2 is the energy generation and transmission sector, average concentrations of this compound in the cold season of a year are 1.5- to 2-fold higher than in summer. The contribution of heating to the volume of emission and, consequently, the concentration of sulphur dioxide was confirmed by the values obtained in the freezing winter of 2005/2006. However, in the second 5-year part of the analysed period, when the winter seasons were cold and very cold (2009/2010, 2010/2011 and 2012/2013), the SO_2 concentrations were not so high. For example, in Tricity, the concentration of SO_2 in the cold winter of 2012/2013 did not diverge much from the concentrations in the last of the analyzed winter seasons, which was warm (IMGW, *www.imgw.pl/extcont/biuletyn_monitoringu/*). Likewise, in Wrocław, the concentration of the SO_2 was slightly lower in the winter season of 2013/2014, classified as very warm, than in the cold season of 2012/2013.

The markedly higher level of pollution with sulphur dioxide recorded in Wrocław is confirmed by the diagrams presenting the frequency of the concentration ranges (Figure 3). In Tricity, the SO_2 concentration was within the lowest class i.e., below 5 μg m^{-3}, for about half of the number of days in the calendar winter, and a rapid decrease in the frequency of occurrence, to about 10%, was found for the range of 11 to 20 μg m^{-3}. In both districts of Wrocław, concentrations from 6 to 10 μg m^{-3} prevailed, and concentrations classified to the subsequent range were recorded more often than the ones in the lowest class (5 μg m^{-3}), which were characteristic for Tricity. In both Gdańsk and Gdynia, concentrations exceeding 25 μg m^{-3} occurred sporadically, whereas concentrations above 35 μg m^{-3} were recorded in Wrocław-Karłowice by 5% more frequently.

The most unfavourable pollutant dispersion conditions are created by thermal blocking layers. Among the factors responsible, Parczewski (1976) lists lower and elevated temperature inversions as well as cases of isotherms and slight (to 0.2°C) vertical gradients of temperature. In the winter seasons of 2004/2005 to 2013/2014, the conditions for pollutant dispersion in both regions were influenced mainly by elevated inversions, which occurred at comparable frequency during daytime and nighttime (Figure 4). The low location of the base of elevated inversion decreases the depth of the air mixing layer, and therefore it limits the dispersion of pollutants. Surface inversions, which directly affect the conditions for dispersion of pollutants from households, although predominant in cities, were recorded less frequently than elevated inversions. Moreover, such inversions were mostly nighttime inversions, recorded almost twice as frequently in Wrocław as in Łeba. Interestingly, the aerological station in Wrocław is located in an urban development

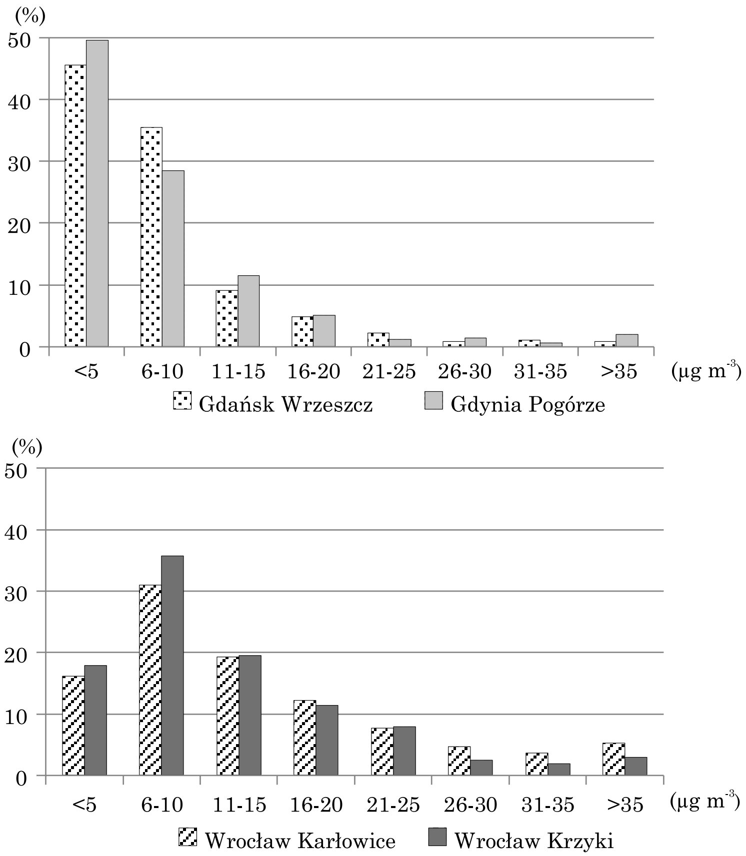

Fig. 3. Frequency of occurrence (%) of the adopted ranges of SO_2 concentrations during the period of calendar winter (December – February). Years 2004/05 – 2013/14

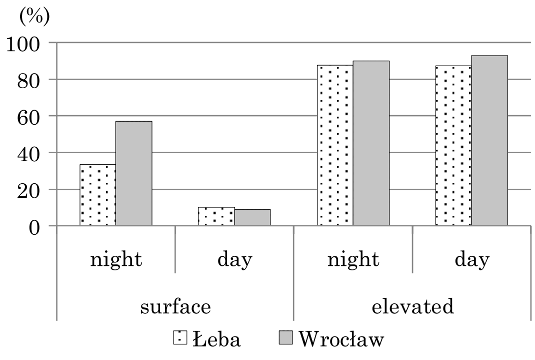

Fig. 4. Frequency of occurrence (%) of the thermal inversions. Years 2004/05-2013/14

area and the thermal structure of the overlying atmospheric boundary level is greatly modified by various factors, mainly terrain roughness and anthropogenic heat emission (LEWIŃSKA 2000, SZYMANOWSKI 2005). As a result, thermal inversions in cities form less frequently than in suburban areas. However, surface inversions occurring more frequently in Wrocław apparently reflect the deteriorating natural ventilation from the north to the south of Poland, connected with the vertical thermal stratification of the troposphere. This is manifested by the decrease in the incidence of an unstable equilibrium and a higher share of the neutral and stable equilibrium, including the most unfavourable conditions for dispersion associated with thermal blocking layers (PARCZEWSKI 1975, 1976). The influence of local conditions that limit the formation of inversions is most likely weaker.

Although surface inversions were recorded more frequently in Wrocław, in vast majority of cases their thickness did not exceed 200 m at either time of the 24-hour measuring period (Figure 1). However, in the area of Łeba, the thickness of nighttime surface inversions was most often double that in Wrocław, namely from 200 to 400 m. On average, the thickness of daytime surface inversions was 200 m. However, in more than 20% of the cases recorded in Łeba, the thickness was comparable to that of nighttime inversions, whereas in Wrocław, such instances were observed only occasionally. Smaller differences between the northern and southern regions of Poland were found in the altitude of the base and the thickness of the first lowest elevated inversion. On average, the base was located at the altitude of the first 1,000 m. Higher location of the base of elevated inversions was recorded in both times of the 24-hour period in Łeba. In most cases (60%), the thickness of the first elevated layer of inversion, which may determine the efficiency of retaining pollutants in the lower layers of air, was less than 200 m. However, in 20% of the cases, the thickness was reported to be twice as large both at night and during the day.

Table 1 contains results of the evaluation of the influence of inversion on the volume and changeability of the sulphur dioxide content in the analysed

Table 1

Coefficients of determination R^2 (%) for statistically significant (at $\alpha = 0.01$) relationship between SO_2 concentration and the characteristics of inversion layers in calendar winter (December – February), in 2004/05 – 2013/14

Station	Characteristics of inversion layers					
	thickness of the surface inversion (m)		the base of the elevated inversion (m agl)		thickness of the first elevated inversion (m)	
	night	day	night	day	night	day
Gdańsk Wrzeszcz	(+) 13.7	·	(-) 6.1	(-) 11.5	(+) 3.5	(+) 3.7
Gdynia Pogórze	(+) 18.2	·	(-) 9.4	(-) 15.7	(+) 4.2	(+) 2.5
Wrocław Karłowice	(+) 4.0	(+) 6.3*	(-) 9.7	(-) 19.5	(+) 3.4	(+) 5.8
Wrocław Krzyki	(+) 3.8	·	(-) 9.1	(-) 14.0	(+) 2.9	(+) 6.0

(+) / (–) relationship positive/negative; * significant at $\alpha = 0.05$; · non-significant at $\alpha = 0.05$

period of 10 winter seasons, supported by single linear regression analysis. The coefficients of determination indicate statistically significant influence, almost exclusively at $\alpha = 0.01$, of the altitude of the base and the thickness of the elevated inversions both in day and at night, and the thickness of the surface inversions at night. The determination coefficients defining the role of elevated inversions are similar in both cities, although the most important feature shaping the variability of SO_2 concentrations is the location of its base during the day. Surprisingly, the impact of the thickness of nighttime surface inversions on sulphur dioxide concentrations in Wrocław is much weaker although such inversions occurred twice as frequently. In comparison to Gdańsk and Gdynia, a relatively small influence can be assigned to this marked prevalence of inversions distinguished by the smallest thickness. The directional coefficients point to the opposing roles of the analysed features and types of inversion layers. An increase in the thickness of inversion layers, both surface and elevated ones, with the lowest location, resulted in a higher sulphur dioxide concentration. However, a positive effect was found for a high location of the base of the elevated inversions. The results documented for the whole winter seasons (December, January and February) were confirmed by the data in individual winter months, both in terms of the direction and the main features of inversion (Table 2). The closest relation-

Table 2

Coefficients of determination R^2 (%) for statistically significant (at $\alpha = 0.01$) relationship between SO_2 concentration and the characteristics of inversion layers according the winter months in 2004/05 – 2013/14

Station	Characteristics of inversion layers					
	thickness of the surface inversion (m)		the base of the elevated inversion (m agl)		thickness of the first elevated inversion (m)	
	night	day	night	day	night	day
December						
Gdańsk Wrzeszcz	·	(+) 13.7	(-) 6.9	(-) 7.6	(+) 3.9	(+) 3.6
Gdynia Pogórze	(+) 6.9	·	(-) 9.8	(-) 7.9	(+) 2.4	(+) 3.8
Wrocław Karłowice	·	·	(-) 3.6	(-) 19.1	·	(+) 2.4*
Wrocław Krzyki	·	·	(-) 5.2	(-) 14.9	(+) 3.9	(+) 2.1*
January						
Gdańsk Wrzeszcz	(+) 29.2	·	(-) 7.4	(-) 22.3	(+) 8.3	(+) 8.9
Gdynia Pogórze	(+) 30.0	·	(-) 10.8	(-) 26.4	(+) 8.7	(+) 5.3
Wrocław Karłowice	(+) 7.1	·	(-) 20.6	(-) 27.8	(+) 7.9	(+) 12.8
Wrocław Krzyki	(+) 11.4	·	(-) 11.6	(-) 20.2	(+) 3.4	(+) 9.4
February						
Gdańsk Wrzeszcz	(+) 10.0	·	(-) 5.0	(-) 7.5	·	·
Gdynia Pogórze	(+) 19.2	·	(-) 8.1	(-) 13.4	(+) 2.2	·
Wrocław Karłowice	(+) 3.1*	·	(-) 8.1	(-) 13.1	(+) 3.3	(+) 2.7
Wrocław Krzyki	(+) 2.7*	·	(-) 12.5	(-) 10.4	(+) 4.1	(+) 7.5

(+) / (–) relationship positive/negative; * significant at $\alpha = 0.05$; · non-significant at $\alpha = 0.05$

ship between the SO_2 concentration and the occurrence of temperature inversions was found in January. In the coldest month of winter, on average, the strongest effect on the sulphur dioxide concentration in both agglomerations was assinged to for the thickness of nighttime surface inversions. However, in the Tricity, this effect, expressed by approximately 30% of the determination coefficients, was about three-fold stronger than in Wrocław. In both agglomerations, values of determination coefficients, over 20%, indicated a positive effect of the high location of the base of elevated inversions at daytime. The strong influence of surface inversions was also determined in February. In December, the altitude of the base of the elevated inversion played a key role in explaining the variability of SO_2 concentrations in both cities.

The main characteristics of inversion, which contribute to an assessment of the causes of sulphur dioxide concentration variability and were distinguished by our analysis of a 10-year period, manifested themselves in most of the analysed winter seasons (Table 3). Most of statistically significant results were obtained for the height of the base of elevated inversions, both

Table 3

Coefficients of determination R^2 (%) for statistically significant (at a = 0.01) relationship between SO_2 concentration and the characteristics of inversion layers in winter seasons (December – February) from 2004/05 to 2013/14

Station	Characteristics of inversion layers					
	thickness of the surface inversion (m)		the base of the elevated inversion (m agl)		thickness of the first elevated inversion (m)	
	night	day	night	day	night	day
1	2	3	4	5	6	7
Winter 2004/05						
Gdańsk Wrzeszcz	(+) 15.9*	·	(-) 10.9	(-) 17.7	·	(+) 17.8
Gdynia Pogórze	(+) 35.4	·	(-) 14.9	(-) 24.9	(+) 11.8*	·
Wrocław Karłowice	·	·	(-) 27.0	·	·	(+) 27.6
Wrocław Krzyki	·	·	·	·	(+) 13.2	·
Winter 2005/06						
Gdańsk Wrzeszcz	(+) 47.1	·	·	(-) 20.6	(+) 13.2	(+) 10.5
Gdynia Pogórze	(+) 40.2	·	(-) 6.4	(-) 28.1	(+) 12.1	(+) 7.7
Wrocław Karłowice	(+) 22.9	·	(-) 11.3	(-) 32.8	·	(+) 13.5
Wrocław Krzyki	(+) 20.0	·	(-) 7.4*	(-) 25.6	·	(+) 11.6
Winter 2006/07						
Gdańsk Wrzeszcz	(+) 30.6	·	(-) 5.6	(-) 5.6	·	·
Gdynia Pogórze	·	·	·	·	(+) 6.4	(+) 7.0
Wrocław Karłowice	·	·	·	(-) 15.4	·	(+) 5.0*
Wrocław Krzyki	·	·	·	(-) 8.5*	·	·

cont. Table 3

1	2	3	4	5	6	7
Winter 2007/08						
Gdańsk Wrzeszcz	(+) 17.5*	·	(-) 12.0	(-) 23.6	·	·
Gdynia Pogórze	(+) 22.3*	·	(-) 13.6	(-) 25.8	·	·
Wrocław Karłowice	·	·	·	·	·	·
Wrocław Krzyki	(+) 26.7	·	(-) 11.5	(-) 21.9	(+) 9.8	(+) 6.2*
	Winter 2008/09					
Gdańsk Wrzeszcz	(+) 27.2*	·	(-) 5.5*	(-) 11.3	·	(+) 5.1*
Gdynia Pogórze	·	·	(-) 8.2	(-) 15.3	(+) 12.1	·
Wrocław Karłowice	·	·	(-) 9.5*	(-) 29.8	·	(+) 11.5
Wrocław Krzyki	(+) 28.2	·	(-) 14.8	(-) 37.6	·	(+) 11.6
Winter 2009/10						
Gdańsk Wrzeszcz	·	·	(-) 4.9*	(-) 4.9*	·	(+) 7.0
Gdynia Pogórze	·	·	(-) 8.2	(-) 8.2	·	(+) 8.4
Wrocław Karłowice	·	·	(-) 30.0	(-) 25.5	·	·
Wrocław Krzyki	·	·	(-) 11.0*	·	·	·
Winter 2010/11						
Gdańsk Wrzeszcz	(+) 30.5	·	·	(-) 18.9	·	·
Gdynia Pogórze	(+) 28.0	·	(-) 7.7*	(-) 21.0	(+) 7.5	·
Wrocław Karłowice	·	·	(-) 24.5	(-) 33.0	(+) 11.8	(+) 12.6
Wrocław Krzyki	·	·	(-) 19.6	(-) 29.7	(+) 15.0	(+) 11.5
	Winter 2011/12					
Gdańsk Wrzeszcz	·	·	(-) 8.5	(-) 20.5	·	(+) 7.7
Gdynia Pogórze	(+) 21.5	·	(-) 12.6	(-) 15.5	·	(+) 12.5
Wrocław Karłowice	·	·	(-) 16.8*	(-) 30.2	·	·
Wrocław Krzyki	·	·	(-) 24.9	(-) 31.0	(+) 13.2*	·
Winter 2012/13						
Gdańsk Wrzeszcz	·	·	(-) 7.6*	(-) 13.3	(+) 7.5*	·
Gdynia Pogórze	·	·	(-) 9.6	(-) 16.4	(+) 6.6*	·
Wrocław Karłowice	·	·	(-) 5.4*	(-) 22.7	·	·
Wrocław Krzyki	·	·	(-) 7.3*	(-) 14.0	·	·
Winter 2013/14						
Gdańsk Wrzeszcz	(+) 40.1	·	(-) 7.4*	(-) 9.0	(+) 14.1	(+) 7.6*
Gdynia Pogórze	(+) 21.9	·	·	(-) 8.1*	·	·
Wrocław Karłowice	·	·	(-) 10.5	(-) 21.3	(+) 5.8*	(+) 6.7*
Wrocław Krzyki	·	·	(-) 11.5	(-) 22.1	(+) 10.1	·

(+) / (–) relationship positive/negative; * significant at $\alpha = 0.05$; · non-significant at $\alpha = 0.05$

nighttime and daytime, although a stronger relationship for daytime was demonstrated in most winter seasons during the ten-year period. The influence of the location of the base of the daytime elevated inversion was most distinct in the winter seasons of 2005/2006, 2010/2011 and 2011/2012. The determination coefficients proved that this characteristic of elevated inversions could explain 20 to 30% of the variability in SO_2 concentrations in both cities. In Wrocław, strong influence of the altitude of the base of daytime upper inversions was manifested also in the winter season of 2008/2009, whereas in Tricity it appeared in 2007/2008. In both agglomerations, nighttime surface inversions were the strongest determinant of sulphur dioxide concentrations in the winter of 2005/2006, when they were the highest. In Tricity, the increase in thickness of nighttime surface inversions contributed to an increase in SO_2 concentrations in over 40% of cases, whereas in Wrocław this relationship was obserevd in about 20% of cases. The significant impact of the thickness of nighttime surface inversion was also manifested, yet only in Gdańsk and Gdynia, in the winter seasons of 2004/2005, 2007/2008 and 2010/2011. High values of determination coefficients indicated the influence of surface inversions even in a warm winter season, e.g. in both cities in 2013/2014 and in Gdańsk-Wrzeszcz also in 2006/2007. In the agglomeration of Wrocław, the negative effect of the thickness of nighttime surface inversions was found only in Wrocław-Krzyki in two consecutive winter seasons of 2007/2008 and 2008/2009. Statistically significant relationships between sulphur dioxide concentrations and the thickness of elevated inversions, indicating the importance of this feature, occurred slightly more often at nighttime. The unfavourable effect of the large thickness of nighttime elevated inversions was manifested in both cities, especially in the winter seasons of 2010/2011 and 2011/2012, and tended to be slightly more evident in Wrocław.

In many publications on the issue of the meteorological conditions of air pollutants dispersion, temperature inversions are listed as the main unfavourable element of anticyclonic weather (Janhäll et al. 2006, İçağa, Sabah 2009, Gramsch et al. 2014, Nidzgorska-Lencewicz, Czarnecka 2015). However, few research papers include statistical assessments of their influence on variations in concentrations of pollutants, and analyses concern mostly surface inversions. Interpretation of references is made difficult by incomparable sources of data (from aerological sounding or acoustic sounding) and different methods of identifying temperature inversions, according to observation series of different lengths, often short ones. Moreover, it is difficult to compare results obtained from different climatic zones and topographic conditions. Despite these difficulties, the results concerning the strength and, above all, direction of correlations between sulphur dioxide concentrations and the analysed types and characteristics of inversions are essentially in line with the results presented in literature. A positive correlation between inversion layers and inversion depths and the surface concentration of pollutants in Athens was shown in research by Katsoulis (1988). Moreover, İçağa and Sabah

(2009) proved that the effect of surface inversions on the SO_2 concentration, similarly to PM10, was almost as strong as that found for air temperature. A significant relationship was demonstrated by Godłowska et al. (2008) between the level of gaseous as well as PM_{10} concentrations and the occurrence of inversion layers, surface and elevated ones, in the urban boundary layer determined on the basis of sodar data. In Kraków, surface inversions capped with elevated inversions of height less than 150 m were of crucial importance in terms of shaping the unfavourable dispersion conditions in the winter months. As for SO_2 and PM_{10}, an increase in their concentration was also recorded in the conditions of a slightly unstable equilibrium, with the elevated layer less than 300 m in height of the base. A strong, negative relationship between the concentration of pollutants and thickness of inversion and the altitude of the base of the lowest inversion, together with an average intensity and duration of inversion, was found in Prague by Knozová (2008). All the above characteristics of inversions strongly affected concentrations of $SO_{2;}$ the influence on CO and NO_x concentrations was found to be weaker, and insignificant in relation to the PM_{10} concentration.

CONCLUSIONS

1. In the winter seasons (December to February) from 2004/2005 to 2013/2014, the concentration of sulphur dioxide in Wrocław was double the one recorded in Tricity, both during the entire 10-year period and in most of the individual winter seasons. In both districts of Wrocław, mean daily values of sulphur dioxide concentrations ranged from 5 to 10 µg m^{-3}, whereas in Tricity the lowest class, i.e. to 5 µg m^{-3}, was predominant. Particular contrasts were found for concentrations exceeding 20 µg m^{-3} which in Wrocław were recorded in approximately 20% of days of the calendar winter, that is four times as frequently as in Tricity.

2. The unfavourable conditions of sulphur dioxide dispersion, connected with temperature inversions, were mainly shaped by the occurrence of elevated inversions recorded mostly at the height of below 1,000 m from the ground level. Surface inversions were formed mainly in the nighttime, almost twice as frequently in Wrocław, although the thickness was most often less than 200 m; in Łeba, the thickness was from 200 to 400 m every second night, on average.

3. Temperature inversions had a statistically significant influence on the variability of sulphur dioxide concentrations in both agglomerations. In most cases, the increase in concentration was recorded most often in the conditions of increasing thickness of nighttime surface inversions. A much weaker impact, albeit significant, was found for the thickness of elevated inversions in both daytime and nighttime. High location of the base of the elevated inversion, particularly in daytime, proved to have a markedly favourable effect.

4. The effect of the altitude of the base and the thickness of elevated inversions on sulphur dioxide concentration in both cities was comparable, whereas the nighttime surface inversions had a much stronger influence in the Tricity, although they were recorded half as frequently as in Wrocław.

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