Environment Protection Engineering

Vol. 43 2017 No. 2

DOI: 10.5277/epe170213

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THE IMPACT OF THERMAL INVERSION ON THE VARIABILITY OF PM_{10} CONCENTRATION IN WINTER SEASONS IN TRICITY

The paper concerns the effect of thermal inversions on PM_{10} concentrations in winter seasons between 2004–2005 and 2012–2013 in Tricity. Temperature inversions were analyzed using aerological measurements timed at 00 UTC and 12 UTC obtained from the aerological station in Łeba. The PM_{10} concentrations were obtained from five Agency of Regional Air Quality stations in the Gdańsk metropolitan area (ARMAAG). The effect of inversion conditions on the variability of daily PM_{10} concentrations was assessed using single and multiple linear regressions. The unfavorable conditions of PM_{10} dispersion in the lower troposphere were mostly determined by elevated inversions, which occurred with comparable frequency, nearly 90%, during the day as well as at night. Surface inversions were recorded at a frequency of 30% at night and only 10% during day-time. The strongest adverse effect on PM_{10} concentrations and their variability during the period of calendar winter was found to be related to the thickness of surface inversions at night. A significant yet substantially less adverse effect during both day and night, however, was found to be related to the thickness of the lowest layer of upper inversion. The high location of the base of upper inversion, primarily during the day-time, contributed to a decrease in PM_{10} concentration.

1. INTRODUCTION

In the troposphere under normal conditions, air temperature decreases with increasing altitude. At times, however, an opposite phenomenon called thermal inversion can be observed. It is characterized by an increase in temperature with increasing altitude. Given the vertical range of the phenomenon, the temperature inversions can be classified into two categories: ground surface inversions and elevated inversions that occur in the free atmosphere [1]. The inversions develop under conditions of high atmospheric

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pressure but are also strongly influenced by topography [2–4]. The analysis of 26 episodes of high PM_{10} concentration, recorded in 2011 and 2012 in Poland and neighboring countries (Germany, the Czech Republic, and Slovakia) show that, although inversions occur in all synoptic situations, their frequency was highest in anticyclonic conditions as a result of the inflow of south-eastern air masses and that almost all cases were accompanied by temperature inversion identified on the basis of aerological sounding [5].

The analysis of the results of aerological or acoustic sounding allows the assessment of the thermal structure of the atmosphere, as well as detection of the thermal inversion and its range. The results of radiosonde measurements were the basis for the research by Parczewski [6] on the detailed characteristics of the conditions of developing, temporal and spatial variability of layers blocking the vertical air mass change. At the Cracow branch of the Institute of Meteorology and Water Management (IMGW), Walczewski conducted pioneering research on the atmosphere with the use of aerological sounding [7]. Another important center, which for over 30 years has been conducting research into the atmospheric boundary layer with the use of sodar, is the Department of Climatology and Atmosphere Protection at the University of Wrocław [8]. The profile of thermal inversions in the surface layer of the troposphere also relies on the results of temperature measurements taken with the use of guyed masts for gradient measurements [9].

Thermal inversion is generally considered to be an unfavorable phenomenon, associated mainly with an increase in the concentration of air pollutants. This is attributed to stable atmosphere stratification present during inversion, which significantly limits vertical air movement, e.g., convection and turbulence, and consequently leads to pollution build-up below the inversion layer [2, 10]. Various publications on winter seasons or episodes with an increased or very high concentration of pollutants point to the presence of inversion layers in the lower part of the atmospheric boundary layers as one of the underlying factors [2, 3, 5, 8, 11–13]. Research on the urban boundary layer in Cracow made with the use of sodar data shows that the most unfavorable conditions of the vertical dispersion of pollutions are connected with stable equilibrium, including the cases of surface as well as elevated inversions [10]. In Gdynia, excessive daily concentrations of particulate matter recorded in the winter of 2005–2006 were directly related to inversion layers present almost every day of January 2006 [11]. The increase in the thickness of the surface inversion resulted in a statistically significant increase in the concentration of particulate matter, whereas the higher location of the base of elevated inversion, particularly during the day-time, contributed to a decrease in PM concentration. In turn, as has been recorded in Prague, the height of the base of inversion and its lingering time had the greatest effect on the concentration of pollutants, while the thickness and intensity of inversion affected the concentration to a much smaller degree [14].

The aim of this paper was to distinguish and assess the role of thermal inversion as a factor in shaping the concentration levels of particulate matter. The selection of the cutoff level of particles of less than 10 µm in diameter, i.e., PM_{10}, as well as of the winter season, is not random. Over a number of years, the annual reports of WIOŚ (Voivodeship Inspectorate for Environmental Protection) [15] and the results presented in the literature [5, 9, 11, 12, 16–18] have shown that the poor quality of air in Poland is mainly caused by PM_{10}, and the standards of concentration are exceeded predominantly in winter. Moreover, it is possible to conduct a longer measuring series for PM_{10} than for $PM_{2.5}$, which, given the high variability of weather conditions in Poland, is an extremely important element of valid (reliable) statistical analysis. Mandatory monitoring of $PM_{2.5}$, i.e., particles of less than 2.5 μm in diameter, has been implemented in Poland only since 2010.

2. MATERIALS AND METHODS

The basic materials for the study included the daily values of PM_{10} concentration covering the period of nine winter seasons (December–February) between 2004–2005 and 2012–2013, obtained from 5 air quality monitoring stations of The Agency of Regional Air Quality Monitoring in the Gdańsk metropolitan area (ARMAAG), located in the Tricity agglomeration [19]. Gdynia and Gdańsk are represented by two stations each, and Sopot by one. Although all stations are defined as urban background stations, those in Gdańsk-Wrzeszcz and Gdynia-Pogórze are located in residential areas: Gdańsk-Jasień among scattered, low-building housing quarters, Sopot in an allotment area and Gdynia-Śródmieście on the harbor waterfront.

The profile of temperature inversion is based on the results of aerological measurements taken at 00 UTC and 12 UTC from the Aerological Station in Łeba, available online [20]. In Poland, the radio sounding measurements are conducted in only three stations (Łeba, Wrocław, Legionowo), and the station located closest to Tricity agglomeration is Łeba – approximately 90 km to the north-west of Tricity. The vertical profiles of air temperature constitute the base for the determination of the thickness of ground (surface) inversion layers, as well as the height of the base and the thickness of the first (lowest) layer in the free (upper) atmosphere at night-time (00 UTC) and day-time (12 UTC). Layers in which the temperature increased with altitude along a vertical temperature gradient, contained a thick surface as well as an elevated inversion. In the case of surface inversion, the layer extended directly from the ground level to the altitude at which the air temperature follows a normal distribution, i.e., it decreases with altitude. Since there may be several layers of elevated inversions in the atmosphere, separated by the layers of air in which the temperature decreases with altitude, this paper takes into consideration only the lowest layer and determines not only its thickness but also its base, i.e., the altitude at which the temperature increase again corresponds to increasing altitude.

The effect of inversion conditions on the variability of daily PM_{10} concentration, including an excessive concentration of over 50 $\mu g \cdot m^{-3}$, was assessed using simple and multiple linear regression analyses and a forward stepwise procedure at the significance levels of $\alpha = 0.05$ and $\alpha = 0.01$. The results were shown using the coefficients of total R^2 and partial determination r^2 in %.

Like most statistical analysis, regression analysis requires variables characterized by a normal probability distribution. The studied series were tested for their convergence with a normal distribution according to the Kolmogorov–Smirnov (K–S) test. This is a test of the null hypothesis stating that the distribution of variables in the test is normal. If the results of the K–S test are statistically significant ($p < 0.05$), then the null hypothesis is rejected and it is assumed that the distribution is not of normal character. The results of the K–S test for the variables characteristic of thermal inversions, as well as for PM_{10} concentrations, proved to be statistically significant, which leads to the conclusion that the distribution of these variables deviates from a Gaussian distribution. Therefore, prior to the regression analysis, the data was transformed so that the distribution is as close to normal as possible. Out of numerous methods of series transformation, the Box–Cox technique was chosen [21].

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

where: $y^{(\lambda)}$ – transformed variable, λ – the main parameter of transformation.

The calculations were made with the use of STATISTICA 12 software.

3. RESULTS AND DISCUSSION

The mean daily PM_{10} concentrations during nine winter seasons ranged from 26 $\mu g\cdot m^{-3}$ in Gdynia Pogórze and Sopot to 43 $\mu g\cdot m^{-3}$ in Gdynia Śródmieście (Fig. 1). However, the absolute maximum daily concentrations recorded in the period under analysis were 6 to 10 times higher than the average. In the districts of Gdynia Śródmieście and Gdańsk Wrzeszcz, the maximum daily concentration was over 300 $\mu g\cdot m^{-3}$. Even though Tricity is a region of lower PM_{10} concentration in comparison with other regions, the daily limit values are nonetheless exceeded there in winter seasons, with significant frequency variations between districts. In Gdynia Śródmieście, the instances of exceeding the daily limit values were recorded during the period 2004–2013 on as many as 30% of calendar-winter days, whereas in other districts of the agglomeration, the frequency was approximately three times lower (Fig. 1). The data presented in Fig. 1 show that excessive daily concentrations of PM_{10} were recorded mainly during the two winter seasons of 2005–2006 and 2009–2010. In Gdynia Śródmieście, exceedance of the limit value due to PM_{10} concentration was recorded on almost 50% of days in 2009–2010.

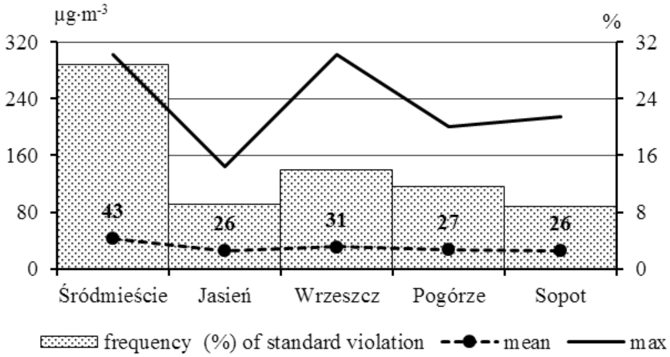

Fig. 1. Characteristics of daily PM_{10} concentration in calendar winter (December–February): – mean, maximum and frequency of standard violation. Period: (2004/2005)–(2012/2013)

High and excessive concentrations of particulate matter occur mainly during the season of artificial heating and, according to the reports of the Environmental Protection Inspectorate (PIOŚ) and the Voivodeship Inspectorate of Environmental Protection (WIOŚ), result from emissions due to combustion, predominantly in the housing and service sectors. The intensity of the processes depends on the course of air temperatures.

Table 1

Number of days with excessive daily PM_{10} concentration against deviations of air temperature from the standard (1951–2000) in winter seasons of (2004/2005)–(2012/2013)

Station	Season								
	2004/2005	2005/2006	2006/2007	2007/2008	2008/2009	2009/2010	2010/2011	2011/2012	2012/2013
Days with excessive concentration									
Śródmieście	31	37	21	25	36	42	14	13	15
Jasień	3	16	1	1	15	19	11	4	4
Wrzeszcz	19	27	8	0	4	22	12	12	9
Pogórze	11	25	5	9	13	23	4	1	3
Sopot	11	22	4	3	7	16	4	5	0
Temperature deviation [°C]									
Gdańsk Rębiechowo	1.9	–2.2	3.1	3.0	0.0	–3.0	–3.0	0.0	–1.2

The thermal conditions of the analyzed series of winter seasons were certainly in line with the profile of the climate of Poland and reflected its high inter-annual variability (Table 1). According to the classification of thermal conditions used by the Climate of Poland Monitoring Bulletin[2], the analyzed 10-year long period includes warm winters (in 2006–2007) and average winters (2008–2009 and 2011–2012), as well as

[2] http://www.imgw.pl/extcont/biuletyn_monitoringu/

very cold winters (2009–2010)–(2010–2011), with the average temperature recorded between December and February varying from that recorded in the period of 1951–2000 by as much as 3 °C. The winter of 2005–2006 was by far colder than the average. The comparison of data presented in Table 1 shows that excessive concentrations of PM_{10} were recorded predominantly in the coldest winter seasons; however, the frequency of excessive concentrations did not occur in the coldest thermal conditions in all districts. Most cases of exceedance of the limit value of particulate matter were recorded in the winter of 2009–2010, which was colder than the average winter by 3 °C. The exceedance of the limit value was recorded with equal frequency in the winter of 2005–2006, even though this season was not as extreme as the winters of 2009–2010 or 2010–2011. In addition, excessive daily concentrations also occurred in warm winter seasons, such as 2006–2007, a fact that points to the effect of other factors on the level and variability of concentration. Air temperature is a factor determining the emission of particulate matter but its effect, i.e., concentration, relies primarily on the meteorological conditions of pollutant dispersion [11, 22]. The state of balance in the atmosphere is particularly important in terms of pollutant dispersion. The most unfavorable conditions for dispersion are linked to temperature inversion, which, according to Parczewski [6], together with the cases of isotherms and a slight (to 0.2 °C) vertical temperature gradient, constitute the so-called thermal blocking layers. The unfavorable effect of temperature inversion is recorded mainly in winter and late autumn, yet it is clearly diversified for particular kinds of pollution due to its distinct properties and other factors affecting the level of concentration [4]. Under inversion conditions, the vertical movement of polluted air is limited as inversions develop in atmospheric calm or weak winds [4, 23]. The analysis of episodes of high concentration of CO, NO, and NO_2 in the winter season in Moscow shows that particularly unfavorable meteorological conditions were related to under obligatory conditions of the surface or an elevated temperature inversion with a lower boundary not higher than 150 m, weak winds with a speed of 1–3 $m\cdot s^{-1}$ and an increased maintenance of concentration when the mixing layers were not thicker than 200 m [24].

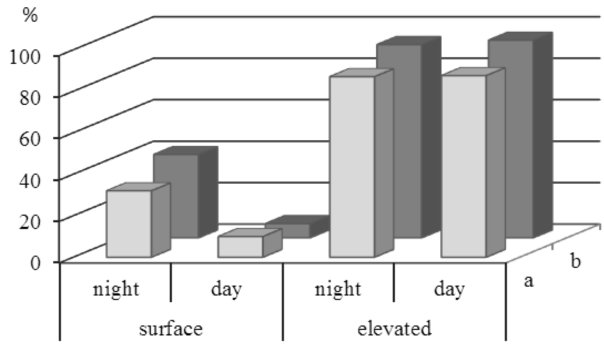

Fig. 2. Frequency of surface and elevated inversion in winter seasons (2004/2005)–(2012/2013) (a), including the days with excessive PM_{10} concentration in Gdynia Śródmieście (b)

The conditions of pollutant dispersion in the lower troposphere in the period from 2004–2005 to 2012–2013 were affected predominantly by elevated inversion layers occurring with similar frequency, i.e., approximately 90%, both during the day as well as night (Fig. 2). Surface inversions were recorded less often, mostly at night-time. The role of inversion conditions in the shaping of PM_{10} concentrations is demonstrated by the fact that the days with an excessive particulate matter concentration in Gdynia Śródmieście were characterized by a 6–8% increase in the frequency of elevated inversions in both night- and day-time, and of surface inversions at night-time.

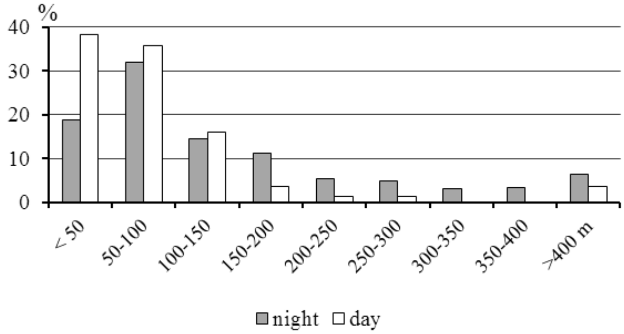

Fig. 3. Thickness of lower layers of inversion – frequency of the adopted ranges during the period of calendar winter (December– February). Period: (2004/2005)–(2012/2013).

Lower inversion layers have a direct effect on the concentration levels of pollutants, particularly those originating with low sources of emission, which are predominant in urban agglomerations [5]. The thickness of surface inversions in the analyzed seasons generally most often reached 100 m (Fig. 3). Inversions of this thickness were recorded at night-time with a frequency of approximately 50%, and at day-time, 70%. The surface inversion thickness at night-time was not more than 50 m, but at night-time a thickness of 50–100 m was predominant. The frequency of an inversion thickness of 100–150 m was similar for day- and night-time (with a slight dominance of day-time inversions). A greater thickness of more than 150 m was recorded mostly at night. The thickest surface inversions at night-time (above 400 m) constituted more than 6% of all cases; however, only 4% reached that thickness during the day as well.

The height of the base of elevated inversion, the location of which is determined by the thickness of the turbulent mixing layer of polluted air, fluctuated widely and reached more than 3000 m (Fig. 4). On 80–90% of days with elevated inversion layers, the base of the first and lowest inversions was at its height not more than 2000 m, and on approximately half of the days it was less than 800 m. The thickness of the first elevated inversion layer generally did not exceed 100 m, and in approximately 85% of cases, 300 m (Fig. 5). The frequency and thickness of the elevated thermal inversion, in contrast with surface inversion, did not show significant differences between day- and night-time. However, day-time was marked by a slightly higher location and a lower thickness of the first elevated inversion layer.

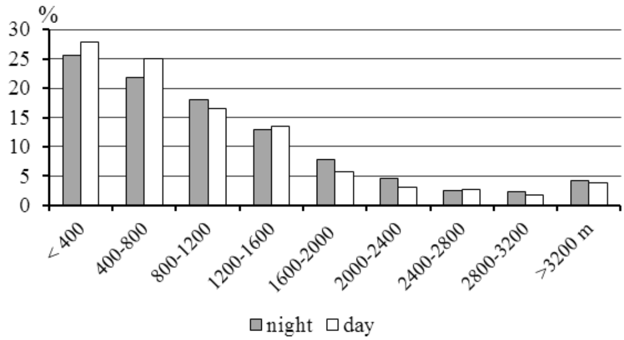

Fig. 4. The base of the elevated inversion layers – frequency of the adopted ranges during the period of calendar winter (December–February). Period: (2004/2005)–(2012/2013)

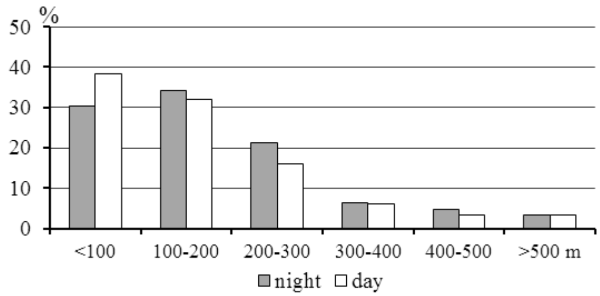

Fig. 5. Thickness of the first (located at the lowest level) elevated inversion layer – frequency of the adopted ranges during the period of calendar winter (December–February). Period: (2004/2005)–(2012/2013)

Table 2

Characteristics of inversion layers in relation with daily PM_{10} (Gdynia Śródmieście) concentration during calendar winter (December–February) in the period (2004/2005)–(2012/2013)

Characteristics	Time of day	The average in days with concentrations of PM_{10}	
		below the standard	exceeding the standard
Thickness of surface inversion, m	night	117	236
	day	76	137
Base of the first elevated inversion (m agl)	night	1254	780
	day	1171	701
Thickness of the first elevated inversion (m)	night	169	237
	day	176	195

The results presented in Table 2 point to the effects of some features of thermal inversion on the level and variability of PM_{10} concentrations in Tricity recorded in nine winter seasons with distinct thermal conditions. The comparison of the main parameters of temperature inversion determined for days with a PM_{10} concentration above as well as below the daily limit (50 $\mu g \cdot m^{-3}$) shows that excessive concentrations were recorded in the more clearly unfavorable condition of a vertical air mass change in the lower troposphere. Unfavorable conditions of dispersion on the days of excessive concentration were, to a great extent, influenced by the greater thickness of surface inversions. A greater thickness and a lower location of the base also characterized these elevated inversions.

Table 3

Coefficients of determination R^2 (%) for statistically significant (at $\alpha = 0.01$) relationship between PM_{10} concentration and the characteristics of inversion layers in calendar winter (December–February) in the period (2004/2005)–(2012/2013)

Station	Characteristics of inversion layers					
	Thickness of the surface inversion (m)		Base of the elevated inversion (m agl)		Thickness of the first elevated inversion (m)	
	Night	Day	Night	Day	Night	Day
Śródmieście	(+) 15.8	(+) 5.2	(–) 8.6	(–) 18.7	(+) 3.6	(+) 2.2
Jasień	(+) 15.8	(+) 6.1	(–) 8.6	(–) 21.8	(+) 5.0	(+) 3.2
Wrzeszcz	(+) 14.2	ns	(–) 8.6	(–) 15.2	(+) 2.9	(+) 2.5
Pogórze	(+) 14.9	(+) 5.7	(–) 10.1	(–) 20.6	(+) 6.3	(+) 3.7
Sopot	(+) 16.0	ns	(–) 11.6	(–) 22.9	(+) 6.0	(+) 3.6

(+)/(-) – relationship positive/negative, ns – non significant at $\alpha = 0.01$.

The influence of the characteristic features of thermal inversion on the pollution of air by particulate matter was confirmed by the results of regression analysis; all directional coefficients presented in Table 3 are significant at $\alpha = 0.01$. In the winter seasons of (2004–2005)–(2012–2013), the concentration of PM_{10} particulate matter was affected to the greatest extent by the location of the first, elevated inversion layer present at daytime, followed by the thickness of the lower layer of surface inversion.

A favorable effect of the high base of elevated inversion on the decrease of PM_{10} concentration is represented by the coefficients of determination within the range of 15–23%. At night-time, the effect of this feature of elevated inversion was approximately two times smaller, and its greater and negative effect on the variability of particulate matter concentration was attributed to the thickness of surface inversion. The influence of day-time surface inversion occurring with a frequency of approximately 10% was considerably weaker. The thickness of the first elevated layer of inversion, which is a decisive factor in the efficacy of blocking the movement and change of polluted air, had a negative effect (not high but statistically significant) on the variability of PM_{10}

concentration. This effect, both for day- as well as night-time, is expressed by a value of R^2 in the range of 2–6.3% [6, 7].

Particularly unfavorable conditions of pollutant dispersion are connected with 24-hour inversions, which mostly occur in the winter months [4, 7]. According to Walczewski [7], in December 2000 as well as in 2002, 24-hour inversions occurred in Cracow on as many as 20 days. In Sibiu (Romania) between 2008 and 2010, a high frequency of inversion was recorded on average in January in at least 10 days, and it was twice less frequent than in December [4]. In the nine analyzed winter seasons (December–February), inversions identified on the basis of results obtained from Łeba were recorded on only 44 days, i.e., in approximately 5% of cases. Given the markedly smaller frequency of surface inversion in comparison with elevated inversion (Fig. 2) and the fact that surface inversions occurred mostly in the cold season, an additional statistical analysis was conducted in order to investigate the relationship between PM_{10} concentration and the thickness of the 24-hour inversion, i.e., recorded both at night- and day-time at 00 UTC and 12 UTC. Regression analysis of the concentration of particulate matter with respect to 24-hour surface inversions was conducted in terms of their thickness both at night- (00 UTC) and day-time (12 UTC), as well as the mean of both times. The best statistical description of the variability of particulate matter concentration was obtained for the mean thickness of 24-hour inversions. The coefficients of determination (R^2) calculated for the individual districts of Tricity were: Śródmieście – 21.3%, Jasień– 34.6%, Wrzeszcz – 20.5%, Pogórze – 20.4%, and Sopot – 19.4%. In contrast with the results presented in Table 4, under the conditions of 24-hour inversion, the thickness of inversions recorded at noon had a stronger influence on particulate matter concentration.

Table 4

Coefficients of determination R^2 [%] and of partial determination r^2 [%] for the relationship between PM_{10} concentration and the characteristics of inversion layers in winter seasons (December–February) from 2004/05 to 2012/13

Station	R^2	r^2			
		Elevated inversion			
		The base of [m agl]		Thickness [m]	
		Day	Night	Day	Night
Śródmieście	21.2	12.3	3.2	ns	0.9
Jasień	24.1	15.5	2.4	ns	1.5
Wrzeszcz	19.0	10.0	3.7	ns	0.7
Pogórze	24.9	12.5	3.4	0.7	2.0
Sopot	28.1	15.5	4.0	0.6	1.7

In another attempt to describe the relationship between PM concentration and conditions of inversion in more detail, the authors undertook a comprehensive assessment of both features of elevated inversions registered, depending on the time of day, with a frequency of 87–95% (Fig. 2), expressed by opposite directional coefficients. The joint effect of the height of the base and the thickness of the first, elevated inversion layer on particulate matter concentration is expressed by coefficients of total determination – from approximately 19% in Gdańsk Wrzeszcz to approximately 28% in Sopot (Table 4). As has already been shown in Table 3, the height of the base of the day-time elevated inversion was a dominant factor in the description of the variability of daily concentrations of particulate matter. The thickness of the lowest lingering layer of elevated inversion, identified through the use of single regression, was similar for both day- as well as night-time. However, this feature of night-time inversion played a statistically significant, yet small, role mainly in explaining PM_{10} concentrations.

Table 5

Coefficients of determination R^2 [%] for the relationship between concentration of PM_{10} and the characteristics of inversion layers in winter seasons (December–February) from 2004/2005 to 2012/2013

Station	Thickness of the surface inversion [m]		Base of the elevated inversion [m agl]		Thickness of the first elevated inversion [m]	
	Night	Day	Night	Day	Night	Day
Winter 2004/2005						
Śródmieście	ns	ns	(–) 12.2	(–) 25.1		ns
Jasień	ns	ns	(–) 8.1 s	(–) 16.4	(+) 8.8	ns
Wrzeszcz	ns	ns	(–) 9.6	(–) 21.3	(+) 8.0	ns
Pogórze	ns	ns	(–) 9.6	(–) 25.5	(+) 8.0	ns
Sopot	ns	ns	(–) 11.6	(–) 24.1	(+) 8.8	ns
Winter 2005/2006						
Śródmieście	(+) 37.8	ns	(–) 11.0	(–) 36.8	(+) 17.0	(+) 12.8
Jasień	(+) 40.4	ns	(–) 8.1 s	(–) 35.3	(+) 10.2	(+) 10.5
Wrzeszcz	(+) 42.2	ns	(–) 12.0	(–) 38.2	(+) 12.1	(+) 13.5
Pogórze	(+) 41.0	ns	(–) 11.9	(–) 38.4	(+) 17.6	(+) 11.5
Sopot	(+) 35.7	ns	(–) 10.7	(–) 41.8	(+) 16.7	(+) 8.1
Winter 2006/2007						
Śródmieście	ns	ns	ns	(–) 8.0 s		
Jasień	ns	ns	(–) 5.7 s	(–) 7.1 s	(+) 8.6	(+) 9.8
Wrzeszcz	ns	ns	(–) 6.5 s	(–) 7.3 s	(+) 9.6	(+) 9.7
Pogórze	ns	ns	(–) 8.6	ns	(+) 6.3	(+) 15.9
Sopot	ns	ns	(–) 10.9	(–) 9.5	(+) 10.0	(+) 14.6
Winter 2007/2008						
Śródmieście	ns	ns	(–) 11.0	(–) 25.7	ns	ns
Jasień	ns	ns	(–) 12.6	(–) 37.5	ns	ns
Wrzeszcz	ns	ns	(–) 24.2	(–) 44.3	ns	ns
Pogórze	ns	ns	(–) 18.0	(–) 40.6	ns	ns

Table 5

Coefficients of determination R^2 [%] for the relationship between concentration of PM_{10} and the characteristics of inversion layers in winter seasons (December–February) from 2004/2005 to 2012/2013

Sopot	ns	ns	(–) 16.7	(–) 41.9	ns	ns
Winter 2008/2009						
Śródmieście	ns	ns	(–) 10.3	(–) 6.5 s		ns
Jasień	ns	ns	(–) 11.2	(–) 12.2	(+) 6.2	ns
Wrzeszcz	(+) 21.6 s	ns	(–) 13.1	(–) 14.8	(+) 9.0	ns
Pogórze	ns	ns	(–) 12.0	(–) 13.3	(+) 17.1	ns
Sopot	ns	ns	(–) 16.4	(–) 11.6	(+) 11.7	ns
Winter 2009/2010						
Śródmieście	(+) 14.8 s	ns	(–) 8.3	(–) 15.7	ns	ns
Jasień	(+) 13.6 s	ns	ns	(–) 8.9	ns	
Wrzeszcz	(+) 13.5 s	ns	ns	(–) 9.1	ns	
Pogórze	(+) 15.7 s	ns	(–) 9.0	(–) 11.2	ns	(+) 4.7 s
Sopot	ns	ns	(–) 9.4	(–) 14.6	ns	ns
Winter 2010/2011						
Śródmieście	(+) 24.4	ns	ns	(–) 38.9	ns	ns
Jasień	(+) 30.9	ns	ns	(–) 36.9	ns	ns
Wrzeszcz	(+) 32.7	ns	ns	(–) 36.4	ns	ns
Pogórze	(+) 28.8	ns	ns	(–) 28.9	ns	ns
Sopot	(+) 27.9	ns	ns	(–) 39.7	(+) 4.8 s	ns
Winter 2011/2012						
Śródmieście	ns	ns	ns	(–) 15.2	ns	(+) 5.8 s
Jasień	ns	ns	ns	(–) 19.6	ns	ns
Wrzeszcz	ns	(+) 13.2 s	(–) 6.0 s	(–) 20.9	ns	(+) 5.1 s
Pogórze	ns	ns	ns	(–) 17.1	(+) 7.1 s	ns
Sopot	ns	ns	ns	(–) 18.2	ns	(+) 6.6 s
Winter 2012/2013						
Śródmieście	ns	ns	(–) 8.2	(–) 9.8	(+) 9.3	ns
Jasień	ns	ns	(–) 17.6	(–) 11.4	(+) 8.7	ns
Wrzeszcz	ns	ns	(–) 15.7	(–) 9.3	(+) 8.3	ns
Pogórze	ns	ns	(–) 20.6	(–) 11.3	(+) 7.6 s	ns
Sopot	ns	ns	(–) 20.5	(–) 11.9	(+) 11.0	ns

Relationships: (+)/(–) – positive/negative, ns – non significant at $\alpha = 0.05$, s – significant at $\alpha = 0.05$, other values R^2 significant at $\alpha = 0.01$.

For individual winter seasons, it was proven that the height at which the elevated inversion layers lingered had a statistically significant role as the feature explaining the effect of thermal inversion on the PM_{10} concentrations with the highest frequency and to the greatest extent (Table 5). In almost all winter seasons and districts under analysis, the greatest influence on PM_{10} concentration was assigned to the location of the base of the elevated layer of day-time inversion. The highest values of the coefficient of determination, in most cases from 35% to 44%, were determined for the seasons of the years 2005–2006, 2007–2008 and 2010–2011 – only the former season was marked by a high frequency of excessive concentration of the daily norms in all districts of Tricity. In most of the winter seasons, the location of the elevated night-time inversion had a significant, yet markedly less important, effect on particulate matter concentration (Table 5). Only the winter season of 2008–2009 was characterized by a similar effect of the height of the base of the first layer of elevated inversion both at day- as well as at night-time. The positive role of the height of elevated inversion postulated in this paper is in line with findings for Cracow by Godłowska et al. [10] based on sodar sounding and determined for not only PM_{10} but also CO, NO and NO_x.

The influence of surface inversion, which occurs less frequently, was found only for three seasons, and the thickness of night-time inversion proved to be significant (Table 5). A particularly strong relationship between PM_{10} concentration and the thickness of night-time inversion was observed during the markedly colder winters of 2005 –2006 and 2010–2011, which were characterized by the most frequent exceedance of the daily limit value (Table 1); in most districts the coefficients of determination ranged from 30 to 40%. A markedly smaller, yet still significant, effect on night-time surface inversion was also found during the winter season of 2009–2010. The thickness of the first elevated inversion layer, lingering at the lowest height, was found to affect air pollution with PM_{10} significantly. This characteristic of elevated inversions, reflecting their "air-tightness" in terms of preventing pollution from escaping the surface portion of air and mixing during both day- and night-time, proved to be a significant factor in all districts of Tricity in the winter seasons of 2005–2006 and 2006–2007, and at night-time during the winter seasons of 2004–2005, 2008–2009 and 2012–2013. A noticeable finding is that during 2006–2007, one of the warmest winter seasons (Table 1), the thickness of the elevated inversion was a feature that illustrated the effect of thermal stratification on air pollution by particulate matter.

It is difficult to measure the obtained results against the numerous data presented in the literature on the subject due to, among other factors, the different methods of determining thermal inversion specified in the Introduction of this paper. Other obstacles are the relatively short period of the present study, often limited to episodes of high and excessive concentration, and the fact that the attempts to assess the effect of inversion are mostly limited to the analysis of a particular synoptic situation or only one feature of inversion. Furthermore, inversions are classified according to various criteria, making it difficult to compare results obtained for different climatic zones and topographic conditions. The most-often presented results concern surface inversions. The increase in PM_{10} concentrations under the conditions of thick night-time surface inversions, as has been proven in this paper, is in line with the results by İçağa and Sabah [12] derived from their analysis of nine winter seasons. They state that the correlation coefficients for the relationship between PM_{10} concentrations and inversions, as defined by daily means, were as high as those obtained for air temperature and significantly higher than those calculated for SO_2. Divergent results are presented by Knozová [14] in research on the influence of temperature inversions on the concentrations of the main pollutants in the air layer less than 50 m in height. The relationship between PM_{10} and the height of the base, thickness, intensity and duration of inversion defined in this way but determined annually, proved to be of weak significance and even statistically insignificant in most cases. A significant influence of inversion conditions on PM_{10} pollution in Sweden was proven by Janhäll et al. [25]. To a great extent, however, temperature inversions affected the decline of particulate matter numbers (in 1 cm^{-3}) between 10 and 368 nm and, to a lesser extent, contributed to a decrease in their concentration [25]. The significant influence of elevated inversions as presented in this paper corresponds to the results by Godłowska et al. [14]. The concentrations of the major gaseous pollutants and particulate matter show the greatest increase in the conditions of stable equilibrium of atmosphere and surface inversions covered with elevated inversions of less than 150 m in height [10].

It should be taken into account that the assessment of the relationship between the concentration particulate matter and the occurrence of temperature inversion, as well as the analysis of the characteristics of this phenomenon, were based on aerological sounding performed by means of open-air measurements. The vertical structure of the boundary layer in urban areas is determined to a large extent by surface roughness, emission of heat from artificial sources, urban heat islands and an increased concentration of pollution [24]. As a result of the mechanical and thermal effects of urban development on the surrounding area, a mixing layer forms over urban areas, whereas temperature inversion is present over non-urban area [9]. Moreover, the topography of the area and land cover affect the intensity, extent and nature of urban inversion [3, 8]. As a result, the role of thermal inversion in providing an explanation for the size and variability of PM_{10} concentrations over urban agglomerations may be greater and even more varied than that presented in this paper.

4. CONCLUSIONS

In the winter seasons (December–February) of 2005–2013, the unfavorable conditions of pollutant dispersion in the lower troposphere were generally caused by elevated inversions occurring with an approximate frequency of almost 90%, both during the day as well as at night. The mean height of the base and the thickness of the day-time inversion layers were lower than those recorded for night-time inversions, but the difference was slight. Surface inversions were recorded with significantly lower frequency than were elevated inversions: three times less frequently at night-time and approximately nine times less frequently at day-time. 24-hour surface inversions were reported rarely, i.e., only 5% of winter days (December–February).

The winter seasons (December–February) of 2004–2005 through 2012–2013 were marked by a statistically significant influence of thermal inversions on PM_{10} concentration, and the location of the base of the elevated day-time inversions was shown to be the strongest factor on these concentrations, followed by the thickness of night-time surface inversions. The unfavorable influence of surface inversions was particularly evident in the conditions of 24-hour inversions. However, due to the much-lower frequency of surface inversions, a comprehensive assessment of unfavorable conditions of pollutant dispersion related to temperature inversion should primarily take into consideration the height of the base of the first, elevated layer of day-time inversion, as well as its thickness and the height of its base at night-time.

ACKNOWLEDGEMENTS

The authors express their thanks to ARMAAG for making the data accessible. Special thanks go to Ms. Ewa Galowska M.A., for the effort of collecting the aerological data.

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