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Anita Bokwa

INFLUENCE OF AIR TEMPERATURE INVERSIONS ON THE AIR POLLUTION DISPERSION CONDITIONS IN KRAKOW

Abstract: Krakow is one of the most polluted cities in Poland. Its natural ventilation is limited due to the location of the city in a river valley. Air temperature inversions are an important element of the local climate in Krakow and a factor strongly influencing air pollution dispersion conditions. Traditional, multi-annual (1972–1996) measurements of air temperature, from three rural stations, and 1-year (03.2009–02.2010) intensive automatic measurements from two rural stations, one urban station and from a mast top 115 m above the ground were used. In the night time, inversions are less frequent in the urban than in the rural area, but still the frequency is over 30% from spring till autumn. In the studied 100-meter air stratum, no crossover effect was found. The relatively high frequency of air temperature inversions in the urban area of Krakow is a significant mesoclimatic difference in comparison with cities located in flat areas. It is also a factor seriously decreasing the natural ventilation and air pollution dispersion conditions.

Key words: urban climate, air temperature inversions, Krakow, air pollution, dispersion
Słowa kluczowe: klimat miasta, inwersje temperatury powietrza, Kraków, zanieczyszczenie powietrza, dyspersja

Introduction

Air pollution emission in a city depends mainly on the number of inhabitants and the magnitude of industrial and transportation emissions. Immission, however, depends mainly on the magnitude of local emissions, on the long-range air pollution transport input and on the conditions of dispersion. The natural factors controlling the air pollution dispersion conditions strongly depend on the landform in which the city is located.

The present paper shows the frequency of air temperature inversions in Krakow, Poland, in the years 1972–1996 and 2009–2010, and their importance in controlling the air pollution dispersion conditions. In spite of numerous improvements, Krakow is still one of the most polluted cities in Poland (Bokwa 2008). Therefore, it is necessary to study the factors which influence the aerosanitary conditions of the city, together with their multi-annual changes. The particular location of Krakow favours the occurrence of air temperature inversions which significantly hinders air pollution dispersion and causes an increase in its concentration.

Krakow is a city in southern Poland, on the Wisla river, with about 750,000 inhabitants. The city's area is 326.8 km^2, and it is located in a concave landform. The historical city centre is placed in the Wisla river valley bottom (at about 200 m a.s.l.), going from the west to the east, and also on a limestone tectonic horst (the Wawel hill), emerging from the river valley. Other parts of Krakow occupy both areas in the river valley with its terraces, and on convex land forms to the south (the Carpathian Foothills, up to 370 m a.s.l.) and to the north (the Krakow-Czestochowa Upland, up to 300 m a.s.l.) of the city centre. The Wisla river valley is narrow in the western part of Krakow (about 1 km) and widens to about 10 km in the eastern part. In the western part there are several limestone tectonic horsts, reaching about 350 m a.s.l. The city area is not surrounded by the hills only from the east, which makes natural ventilation difficult (German 2007). According to J. Walczewski *et al.* (2000), the main meteorological factors controlling the air pollution dispersion conditions in Krakow are:

1) prevalent low wind speed, i.e. poor horizontal ventilation;
2) high intensity and varied vertical range of air temperature inversions, i.e. limited vertical ventilation;
3) precipitation washing out air pollution;
4) synoptic situation.

Previous studies on air temperature inversions in Krakow

Various methods are used to study the vertical structure of air temperature above a city. Sensors are located on towers, either already existing or constructed especially for the need of a particular study. Balloons and airplanes are used for mobile measurements of larger vertical and horizontal extent. Sodar measurements allow to obtain information of only qualitative character. Another method, used in cities located in valleys, is a comparison of the data from stations located 2 m above the ground, in various places in the cross-section of a valley with similar land use. J. Walczewski (1994) showed that the results from the "surface profiles" and e.g. balloon sounding are in a good accordance. Regardless the landform in which the city is located, usually during the night time, the isothermal or adiabatic lapse rate can be observed over the urbanised area while in rural areas an inversion occurs at the same time (Bornstein 1968, Oke 1982 after: Godowitch *et al.* 1985). Additionally, in cities located in valleys, katabatic flows can occur and significantly modify the air temperature spatial pattern in comparison with cities located in flat areas (e.g. Hildebrand, Ackerman 1984; Dupont *et al.* 1999; Kolev *et al.* 2000).

The first studies on air temperature inversions in Krakow were organised by W. Milata and later described in the work of his wife, also engaged in the research. W. Milata compared the data from the city centre and the river valley bottom (i.e.

from the climatological station of the Jagiellonian University in the Botanical Garden) with the data from a non-urban station, located about 100 m higher, south of the city centre (Libertow). He pointed out the limited possibilities of such a comparison due to differences in both relief and land use between the stations. Nevertheless, he found out that an inversion occurred during about 200 days per year and reached a mean intensity of 1.3°C (Milata 1959).

In the years 1970 and 1972, measurements of the vertical thermal structure above Krakow, up to 3000 m, were performed with an airplane. Ground inversions can occur at any hour during the day, in anticyclonic synoptic situations they reach 50–800 m above the ground and in cyclonic ones 100–600 m, most often 200 m (Morawska-Horawska 1978). Measurements organised in the years 1975–1976 showed that the urban heat island (UHI) reduced ground inversions or raised their upper limit (Lewińska 1979). In the years 1978 and 1979, the vertical structure of air temperature above the city and in rural areas nearby, up to 500 m above the ground, was studied using balloons. Parallel measurements in the network of stations located 2 m above the ground, at various relative heights in the valley, were performed (Lewińska, Zgud 1980; Lewińska 1984). Both methods gave similar results and the UHI vertical extent was estimated at 100–200 m in the cold half year and over 200 m in the warm half year. The inversion layer height reached a maximum of 300 m in the mornings and 100 m in the evenings. The emission of anthropogenic heat in the urban canopy layer increased the frequency of ground inversions up to 50 m high, even during the day time, which was not observed in rural areas. J. Walczewski (1994) summarised various studies concerning the vertical structure of air temperature over Krakow. The height of ground inversions was estimated in a broad range of 60–200 m. Sodar measurements realised in Krakow since 1980, allowed to find out that an inversion may last a whole day and night even as often as 20% of all days. In winter, inversions 150–300 m high dominated, and above them the elevated inversions were observed. In summer, the height increased up to 800 m (Walczewski 1984, 1994, Walczewski *et al.* 2000). K. Dębicka (1998, 1999) concluded that in every season the frequency of nights with inversion reaches about 70%. M. Morawska-Horawska (1978) showed that the height of an inversion's impact on air pollution dispersion is linked with the height of two groups of emitors. Most chimneys are located on the roofs of houses, only a few industrial chimneys are higher than 200 m.

The studies presented above showed the occurrence of temperature inversions in Krakow and their importance in controlling air pollution dispersion. However, after 1989, a significant decrease in anthropogenic heat emission took place in Krakow, which caused changes in the horizontal air temperature spatial pattern (Bokwa 2010). Therefore, the present paper is an attempt of showing the present inversion occurrence and possible changes compared to 1970s and 1980s.

Data and methods

The study was based on multi-annual data from standard meteorological stations, and on 1-year data from automatic measurements. The multi-annual data consist of daily minimum air temperature from the stations in Balice, Libertow and Garlica Murowana, from the years 1972–1996. The stations are located in rural areas around Krakow and represent various land forms:

1) Balice: 237 m a.s.l., in the river valley bottom, the airport station placed west of the city (50°05'N, 19°48'E);
2) Libertow: 314 m a.s.l., on a hill top south of the city (49°58'N, 19°54'E);
3) Garlica Murowana: 270 m a.s.l., on a hill top north of the city (50°09'N, 19°56'E) (Fig. 1).

The stations form a cross-section of the Wisla river valley and the minimum air temperature is supposed to be representative for the night time. A. Bokwa (2009) studied air temperature inversions in the Krakow area, but later (Bokwa 2010) it

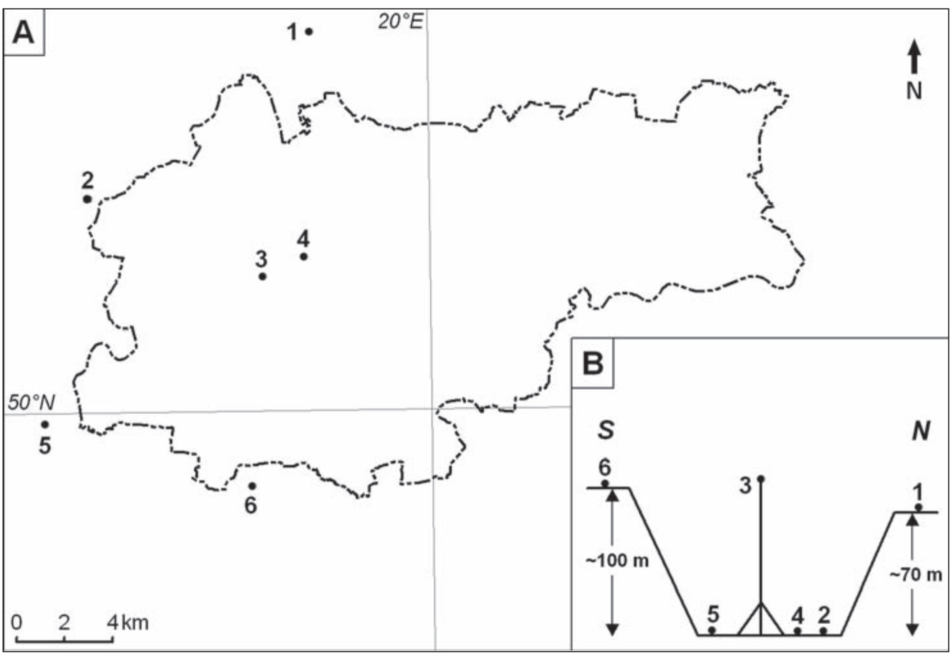

Fig. 1. Location of measurement points: A. in the area of Krakow and its vicinities, B. in the N-S profile (a scheme)

Ryc. 1. Rozmieszczenie punktów pomiarowych: A. na obszarze Krakowa i okolic, B. schematycznie w profilu N-S

Explanations: 1 – Garlica Murowana, 2 – Balice, 3 – the mast, 4 – Krasinskiego St., 5 – Jeziorzany, 6 – Libertow; dashed line – city border.

Objaśnienia: 1 – Garlica Murowana, 2 – Balice, 3 – maszt, 4 – Al. Krasińskiego, 5 – Jeziorzany, 6 – Libertów; linia przerywana – granica miasta.

Opracowanie ryciny: / *Figure by*: J. Walawender, A. Bokwa.

was found out that not all the stations in rural areas around Krakow are rural indeed; in some cases the local climate is strongly influenced by the city, in spite of quite a large distance from the city borders. That is why the analysis is limited only to the western part of the valley. Differences in the minimum air temperature between Balice and Libertow or Garlica Murowana were used to determine the occurrence of air temperature inversions. The differences <-0.5K were classified as an inversion situation. Additionally, for the period 09.2007–08.2009, air temperature in Balice and Libertow measured at 00 and 03 UTC was used.

The automatic measurements of air temperature were organised using both ground measurement points and a broadcast mast. An air temperature sensor (Davis Instruments) was attached 115 m above the ground (335 m a.s.l.), on a mast which is located in the western part of the city, in the border zone between built-up and green areas. Another air temperature sensor (HOBO Onset type) was installed at the base of the mast (222 m a.s.l.), 2 m above the ground, in the radiation shelter. Automatic measurements at a height of 2 m above the ground were also organised in the already mentioned Libertow, and in:

1) Jeziorzany: 211 m a.s.l., a rural point close to Balice but without an influence of the airport buildings (49°59'N, 19°46'E);
2) Krasinskiego St.: 204 m a.s.l., Krakow city centre, a street canyon (50°03'N, 19°55'E) (Fig. 1).

Measurements on the mast were taken every 10 minutes, and at the ground measurement points – every 5 minutes. Synchronous measurement results from all the points were available for the following periods:

1) spring: 29.03–19.05.2009;
2) summer: 1.06–29.08.2009 (mast's profile, Krasinskiego St. and Libertow), 16.07–29.08.2009 (Jeziorzany);
3) autumn: 7.09–30.11.2009;
4) winter: 1.12–12.02.2010.

Results

In the years 1972–1996, inversions were much more frequent in the case of the Balice–Libertow profile than in the case of the Balice–Garlica Murowana profile (Table 1). Garlica Murowana is located about 45 m lower than Libertow and the results obtained suggest that the inversion level is often located in such a way that Garlica is below and Libertow above it. It also proves that generally the inversion height is quite low, up to 100 m above the valley floor.

Similarly to the minimum air temperature, measurements at 00 and 03 UTC also represent the thermal conditions of the night time. The comparison of the data presented in Table 1 and 2 shows an increase in the frequency of inversion occurrence between the periods 1972–1996 and 09.2007–08.2009, from about 50% to 70%. However, it cannot be interpreted as a change in the thermal conditions of the study area. The reason for the difference is a slight change in the location of the station in Balice. The recent results are more reliable than the previous ones (Bokwa 2010).

Table 1. Seasonal frequency [%] of air temperature inversions based of the minimum air temperature differences between Balice and Libertow (B–L) and between Balice and Garlica Murowana (B–GM) in the years 1972–1996

Tab. 1. Sezonowa częstość [%] inwersji temperatury powietrza wyznaczonych na podstawie różnic temperatury minimalnej między Balicami i Libertowem (B–L) oraz Balicami i Garlicą Murowaną (B–GM) w latach 1972–1996

Season	B–L	B–GM
Spring	46.1	24.5
Summer	54.0	16.8
Autumn	50.1	23.0
Winter	44.3	32.2

Table 2. Seasonal frequency [%] of air temperature inversions based of the air temperature differences between Balice and Libertow at 00 and 03 UTC, in the period 09.2007–08.2009

Tab. 2. Sezonowa częstość [%] inwersji temperatury powietrza wyznaczonych na podstawie różnic temperatury między Balicami i Libertowem o godz. 00 i 03 UTC w okresie 09.2007–08.2009 r.

Season	n	00 UTC	03 UTC
Spring	184	74.5	92.4
Summer	184	69.0	70.6
Autumn	182	75.3	72.5
Winter	181	70.7	71.8

Explanations: n – number of days.

Objaśnienia: n – liczba dni.

The results of the automatic measurements were used first to compare the mast top (335 m a.s.l.) and Libertow (314 m a.s.l.). Figure 2 shows that in every season, in the night time, the air temperature in Libertow is lower on average by about 1–2K than at the mast top while in the day time it is higher by about 2–3K. Libertow is often the warmest point of the Krakow area (Bokwa 2010), so the results show that both Libertow and the mast top are usually above the inversion layer but the sensor at the mast is additionally effected by the anthropogenic heat emitted by the urban area of Krakow. It can be assumed that the data from Libertow show the conditions of the boundary layer in the rural area while the data from the mast top in urban area. Then the results for the night time are in accordance with those of R. D. Bornstein (1968) who showed that the temperature difference between urban and rural areas decrease with height and diminish at about 300 m above the ground (the crossover effect). The measurements in Libertow and on the mast top are not completely comparable because the sensor in Libertow is not only about 100 m above the valley bottom, but also 2 m above the ground. However, the studies by J. Lewińska *et al.* (1982) and J. Lewińska (1984), based on various techniques, gave similar results. Additionally, she showed that the crossover effect occurs in Krakow at about 200 m above the ground.

The differences in air temperature <-0.5K between Jeziorzany and Libertow were used to determine the occurrence of temperature inversions in the rural areas west of Krakow, while the differences between Krasinskiego St. and the mast top – in the urban area of the city. Figure 3 shows the frequency of temperature inversions in both areas, for every hour. In spring and summer, the inversions occurred during the night time in the urban area in 40–50% of all measurements for an hour, while

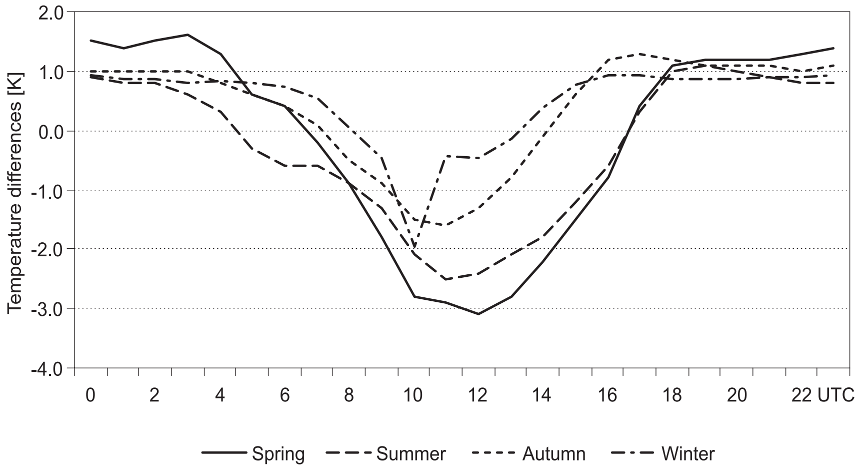

Fig. 2. Mean hourly air temperature differences [K] between the mast top and Libertow in particular seasons of the year in the period 03.2009–02.2010

Ryc. 2. Średnie godzinne różnice temperatury powietrza [K] między szczytem masztu i Libertowem w poszczególnych porach roku w okresie 03.2009–02.2010 r.

Źródło: / *Source*: Bokwa 2010.

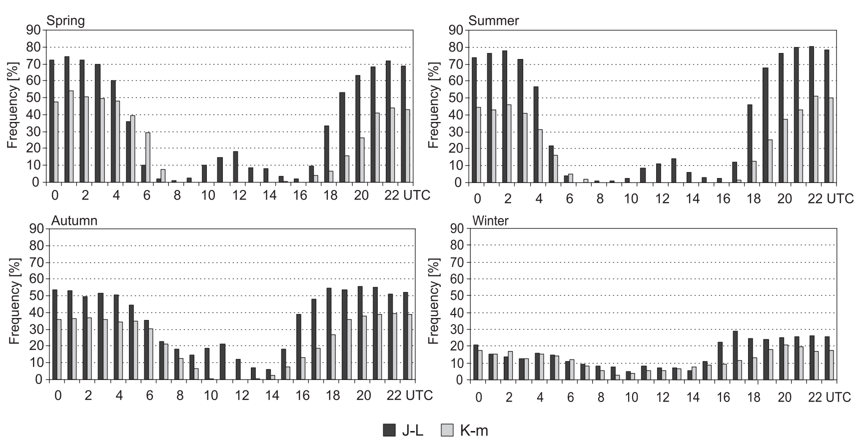

Fig. 3. Frequency [%] of air temperature inversions in urban (K–m) and rural (J–L) areas, for particular seasons and hours in the period 03.2009–02.2010

Ryc. 3. Częstość [%] inwersji temperatury powietrza w obszarach miejskich (K–m) i pozamiejskich (J–L) w poszczególnych porach roku i godzinach w okresie 03.2009–02.2010 r.

Explanations: J – Jeziorzany, L – Libertow, K – Krasinskiego St., m – top of the mast.

Objaśnienia: J – Jeziorzany, L – Libertów, K – Al. Krasińskiego, m – szczyt masztu.

Źródło: / *Source*: Bokwa 2010.

in the rural area in 70–80%. In autumn the values decreased to 30–40% in the urban area and 50–60% in the rural area. Inversions were the least frequent in winter and the values for both areas were almost the same: 10–20%. During the day time, inversions occurred in 10–20% of cases, from spring to autumn only in the rural area, and in winter also in the urban area. The temperature differences were used to calculate the vertical lapse rates. Table 3 shows that high values of the vertical lapse rate (i.e. $<-4.0K \cdot 100\ m^{-1}$) are quite common but during the night time. In summer, in the urban area, they practically do not occur at all. In spring and autumn such situations were much more frequent in the rural area. Those results are in accordance with earlier findings that the vertical lapse rates are much lower over urban areas than in rural areas.

Table 3. Seasonal frequency [%] of air temperature inversions with the lapse rate $<-4.0K \cdot 100\ m^{-1}$ in urban and non-urban areas, in the western part of the Wisla River valley within the Krakow area, at particular hours UTC, in the period 03.2009–01.2010

Tab. 3. Sezonowa częstość [%] inwersji temperatury powietrza o gradiencie pionowym $<-4,0K \cdot 100\ m^{-1}$ w obszarze miejskim i pozamiejskim, w zachodniej części doliny Wisły na terenie Krakowa i okolic, w poszczególnych godzinach UTC, w okresie 03.2009–01.2010 r.

UTC hour	Spring		Summer		Autumn		Winter	
	J–L	K–m	J–L	K–m	J–L	K–m	J–L	K–m
0	34.7	6.4	18.8	0.0	23.6	5.0	2.9	1.8
1	37.6	5.3	17.4	0.0	23.8	6.0	0.5	3.4
2	34.6	7.3	17.2	0.0	23.2	8.1	0.0	3.1
3	33.2	12.2	15.7	0.0	22.0	8.1	0.0	2.8
4	20.9	8.2	7.9	0.0	19.1	6.9	0.0	3.0
5	5.1	7.5	0.0	0.0	16.5	5.9	0.0	1.0
6	0.2	1.2	0.0	0.0	12.2	5.6	0.0	0.0
7	0.0	0.0	0.0	0.0	7.5	3.9	0.0	0.0
8	0.0	0.0	0.0	0.0	5.8	1.6	0.0	0.0
9	0.0	0.0	0.0	0.0	2.9	0.7	0.0	0.0
10	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0
16	0.0	0.0	0.2	0.0	3.4	0.0	0.0	0.0
17	0.2	0.0	0.0	0.0	10.4	0.5	0.0	0.0
18	3.0	0.0	1.4	0.0	17.4	0.7	0.8	0.0
19	11.7	0.0	12.4	0.0	20.9	1.5	1.8	2.0
20	17.8	0.4	18.6	0.0	22.9	3.2	4.5	0.5
21	24.4	0.2	21.7	0.0	22.4	4.3	4.5	3.0
22	30.3	0.9	26.0	0.4	21.6	4.6	3.3	3.1
23	31.0	4.1	22.1	0.0	21.5	6.8	0.5	3.2

Explanations: J – Jeziorzany, L – Libertow, K – Krasinskiego St., m – top of the mast.
Objaśnienia: J – Jeziorzany, L – Libertów, K – Al. Krasińskiego, m – szczyt masztu.

Conclusions

The results presented above are in principle in accordance with the results by J. Lewińska *et al*. (1982) and J. Lewińska (1984), however J. Lewińska used balloon soundings and they were performed in the eastern part of the river valley, while in the present project the measurements come from constant heights and from the western part of the valley. What is worth mentioning is the relatively high frequency of inversions above the urban area in comparison with the rural area. Many authors claimed that the UHI forces the occurrence of an almost isothermal situation above a city in the night time, while in the rural areas nearby a strong inversion usually develops. But that is true for cities whose mesoclimate is not influenced by a complicated relief (Landsberg 1981). In Krakow inversions are less frequent in the night time than in the rural areas, but still the frequency is over 30% from spring till autumn. In the studied 100-meter air stratum, no crossover effect was found, i.e. the air temperature in the whole rural profile was lower than in the urban one. The relatively high frequency of air temperature inversions in the urban area of Krakow is a significant mesoclimatic difference in comparison with cities located in flat areas. It is also a factor seriously decreasing the natural vertical ventilation conditions. The inversions in Krakow are often quite low and of large vertical lapse rate which means that the air pollution from the local heating facilities and transportation sources is trapped within the river valley. A further supply of the polluting substances causes their very high concentrations and that is the reason why in the city centre, in Krasinskiego St., the mean annual PM_{10} concentration reached 80 $\mu g \cdot m^{-3}$ in 2008, while the allowed limit is 40 $\mu g \cdot m^{-3}$ (*Raport*... 2009). Therefore, the actions aimed at improvement of the aerosanitary conditions should concentrate on decreasing air pollution emissions and increasing the city's ventilation with a long-term spatial planning strategy.

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Rola inwersji temperatury powietrza w kształtowaniu warunków dyspersji zanieczyszczeń powietrza w Krakowie

Streszczenie

Kraków nadal należy do miast o największym zanieczyszczeniu powietrza w Polsce, przykładowo: w Al. Krasińskiego w 2008 r. średnie roczne stężenie PM_{10} osiągnęło 80 $\mu g \cdot m^{-3}$, przy obowiązującej normie 40 $\mu g \cdot m^{-3}$ (*Raport*... 2009). Dyspersja zanieczyszczeń powietrza jest znacznie osłabiona przez usytuowanie miasta w dolinie Wisły i częste inwersje termiczne.

W pracy wykorzystano codzienne pomiary temperatury minimalnej z lat 1972–1996 ze stacji meteorologicznych w Garlicy Murowanej (270 m n.p.m.), Balicach (237 m n.p.m.) i Libertowie (314 m n.p.m.), automatyczne pomiary temperatury co 5 minut z okresu 03.2009–02.2010 r. z punktów w Jeziorzanach (211 m n.p.m.), przy Al. Krasińskiego (204 m n.p.m.) i przy ul. Malczewskiego (222 m n.p.m., u podnóża masztu radiowego) oraz automatyczne pomiary co 10 minut z masztu radiowego przy ul. Malczewskiego (wys. 115 m n.p.g.) z tego samego okresu (Ryc. 1). Ponadto wykorzystano pomiary temperatury powietrza w Balicach i Libertowie o godz. 00 i 03 UTC z okresu 09.2007–08.2009 r. Stacje w Garlicy Murowanej, Balicach i Libertowie tworzą profil N-S przez zachodnią część doliny Wisły w obszarach pozamiejskich Krakowa. Punkt w Jeziorzanach reprezentuje tereny pozamiejskie w dnie doliny, podobnie jak Balice, ale jest pozbawiony wpływu zabudowy lotniska. Punkt przy Al. Krasińskiego reprezentuje warunki kanionu ulicznego w centrum miasta, w dnie doliny. Za sytuację inwersyjną przyjęto taką, kiedy różnica temperatury między stacją w dnie doliny i stacją wierzchowinową lub punktem na maszcie wynosiła <-0,5K.

W latach 1972–1996 inwersje zdarzały się znacznie częściej w profilu Balice–Libertów niż Balice–Garlica Murowana (Tab. 1). W porównaniu z latami 1972–1996, w okresie 09.2007–08.2009 r. częstość występowania inwersji wzrosła z około 50% do 70% (Tab. 1 i 2), jest to jednak tylko efekt niewielkiej zmiany lokalizacji stacji w Balicach (Bokwa 2010). Porównanie równoczesnych pomiarów z Libertowa i wierzchołka masztu (Ryc. 2) pokazuje, że nocą temperatura w Libertowie jest niższa o około 1–2K. Różnice temperatury <-0,5K między Jeziorzanami i Libertowem wykorzystano do określenia częstości występowania inwersji w obszarze pozamiejskim, zaś różnice między Al. Krasińskiego i szczytem masztu – w obszarze miejskim. Nocą inwersje występują rzadziej nad obszarem miejskim niż pozamiejskim, ale ich częstość przekracza 30% od wiosny do jesieni (Ryc. 3). Duże wartości pionowego gradientu temperatury (tzn. $<-4{,}0\mathrm{K}\cdot 100\ \mathrm{m}^{-1}$) występują znacznie częściej w obszarze pozamiejskim niż nad miastem (Tab. 3). W badanej 100-metrowej warstwie powietrza nie stwierdzono tzw. efektu *crossover*. Relatywnie duża częstość inwersji termicznych nad zurbanizowanym obszarem Krakowa stanowi ważną różnicę mezoklimatyczną w porównaniu z klimatami miast położonych na obszarach o mało zróżnicowanej rzeźbie terenu. Jest to także czynnik poważnie ograniczający warunki dyspersji zanieczyszczeń powietrza.

Anita Bokwa
Jagiellonian University
Institute of Geography and Spatial Management
Gronostajowa 7, 30–387 Krakow, Poland
anita.bokwa@uj.edu.pl