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Impact of Natural and Anthropogenic Factors on Fog Frequency and Variability in Kraków, Poland in the Years 1966–2015

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ABSTRACT

The aim of the study was to determine the long term variability of fog occurrence in Kraków in the light of the changeability of fog favoring factors. The annual number of days with several fog characteristics was studied for the period 1966–2015, using data from two meteorological stations located in the city center and in the suburbs. For all these data series on fog, a strong decrease was observed in the study period, i.e., the number of days with fog decreased on average by about 60%, with the tendency being more distinct in the city center. Fog favoring conditions were determined by atmospheric circulation, wind speed, relative humidity, urban heat island (UHI) and air pollution and correlated with data on fog. Results statistically significant at $p < 0.01$ show that the relationship is the strongest between fog frequency and air pollution. However, as the air pollution levels decreased, especially after the change of political and economic system in 1989, environmental factors became decisive in controlling fog occurrence. Although the role of atmospheric circulation in fog formation is unquestionable, fog favoring circulation types (Sa, SWa, Ca, Ka) show no meaningful tendency and no significant correlation with long-term fog occurrence frequency. Therefore, decreasing trends in days with low wind speed and in days with relative humidity RH ≥ 80% and RH ≥ 95% are considered as additional factors which contributed to the observed fog frequency decrease. UHI showed no impact on fog frequency as in Kraków relief modified UHI (RMUHI) is observed and no significant changes in the part of UHI defined for the lowest part of the city were observed.

Keywords: Fog; Air pollution; Atmospheric circulation; Relief modified urban heat island.

INTRODUCTION

Urban structures modify local climate significantly (e.g., Landsberg, 1981) but in the case of some climatic elements, e.g., precipitation or fog, the documented impacts show converse results. Ayers and Levin (2009) and Levin and Brenguier (2009) summarized the works concerning air pollution and precipitation and concluded that most studies dealt with the effects of aerosol on clouds whilst few regarded the effects of pollution on the amount of precipitation on the ground. The overall effects of cities on precipitation appear not to be clearly connected with aerosol pollution and the connection between aerosol concentration and the amount of precipitation on the ground is not yet clear. The results vary widely between increases in rainfall, decreases in rain amounts and no connection at all. Sachweh and Koepke (1995) summarized papers on fog and concluded that urban areas either decrease or increase (up to 100%) the fog frequency, depending on the city studied. The main factors which affect fog occurrence in urban areas are as follows:

- urban heat island (UHI) magnitude (e.g., Sachweh and Koepke, 1995, 1997; LaDochy, 2005; Shi *et al*., 2008; Witiw and LaDochy, 2008; Li *et al*., 2012);
- air humidity (e.g., Sachweh and Koepke, 1995; Shi *et al*., 2008; Li *et al*., 2012);
- wind speed (e.g., Sachweh and Koepke, 1997);
- aerosol concentrations (e.g., Appel *et al*., 1985; Oke, 1987; Sachweh and Koepke, 1995; LaDochy, 2005; Shi *et al*., 2008; Witiw and LaDochy, 2008; Li *et al*., 2012).

In the case of cities located, for example, at the seaside or in the mountains, additional factors need to be included, e.g., atmospheric circulation (Witiw and LaDochy, 2008), ice cover of the sea waters (Gough and He, 2015) or cold air pool occurrence in the valleys (Scherrer and Appenzeller, 2014). The interactions among the factors mentioned are complex, and in particular circumstances, the importance of a given factor may change; for example, Shi *et al*. (2008)

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showed that the impact of a city on fog formation depends on the stage of the city's development. Sachweh and Koepke (1995) suggested that the atmospheric effects which decrease fog, such as increasing temperature or moisture deficit, might outweigh those that promote fog, such as increasing aerosol concentration or decreasing winds.

Kraków, Poland, is a city where large changes in both fog frequency and the factors important for fog occurrence have been observed within the latest decades. The urban climate of Kraków has been additionally affected by industrial factors, e.g., by the construction and operation of a huge steelworks during the communist period, followed by the economic crisis and then a large drop in production after the change of political and economic system in 1989, or by huge changes in air pollution with particulate matter. Moreover, it is significantly influenced by the relief as the city is located in a valley and built-up areas can be found in both concave and convex landforms. Therefore, the aim of the paper is to estimate the role of particular natural and anthropogenic factors in long-term changes in fog occurrence in Kraków in the 50-year period 1966–2015.

STUDY AREA

Kraków is located in southern Poland, on the Vistula River (Wisła), with an area of 326.8 km^2 and the number of inhabitants reaching 762 thousand (data of Dec. 2014; Rocznik Statystyczny Krakowa, 2015). The territory of Kraków belongs to three different geomorphological regions, which is clearly seen in the relief of the area (Fig. 1). The city's central part, with the Vistula river valley, is located at an altitude of about 200 m a.s.l. In the western part, the valley is as narrow as 1 km as it is enclosed by hills reaching over 100 m above the valley floor. However, in the eastern part of the city, the valley widens to about 10 km and there is a system of river terraces. The hilltops bordering the city to the north and the south reach about 100 m above the river valley floor, similar to the hilltops in the valley which means that the city is located in a concave land form. The local climate processes linked to the impact of relief include, for example, katabatic flows, cold air reservoir formation, frequent air temperature inversions, much lower wind speed in the valley floor than at the hilltops and abundant air pollution (e.g., Hess, 1974; Walczewski, 1994). Land use/land cover of the city is dominated by agricultural areas (i.e., arable lands, orchards, meadows), which constitute 49% of the city's administrative area. The second largest share of 31% includes built-up areas together with urban green spaces. Transportation areas cover 10% of Kraków's area and the remaining 10% belongs to forests (5%), water bodies (2%) and other areas (3%) (Bokwa, 2010). The land use/land cover structure described might be regarded as favorable for frequent fog occurrence due to the relatively high percentage of areas covered with vegetation, which are able to provide large amounts of water vapor to the air mainly during the vegetation period due to evapotranspiration, but

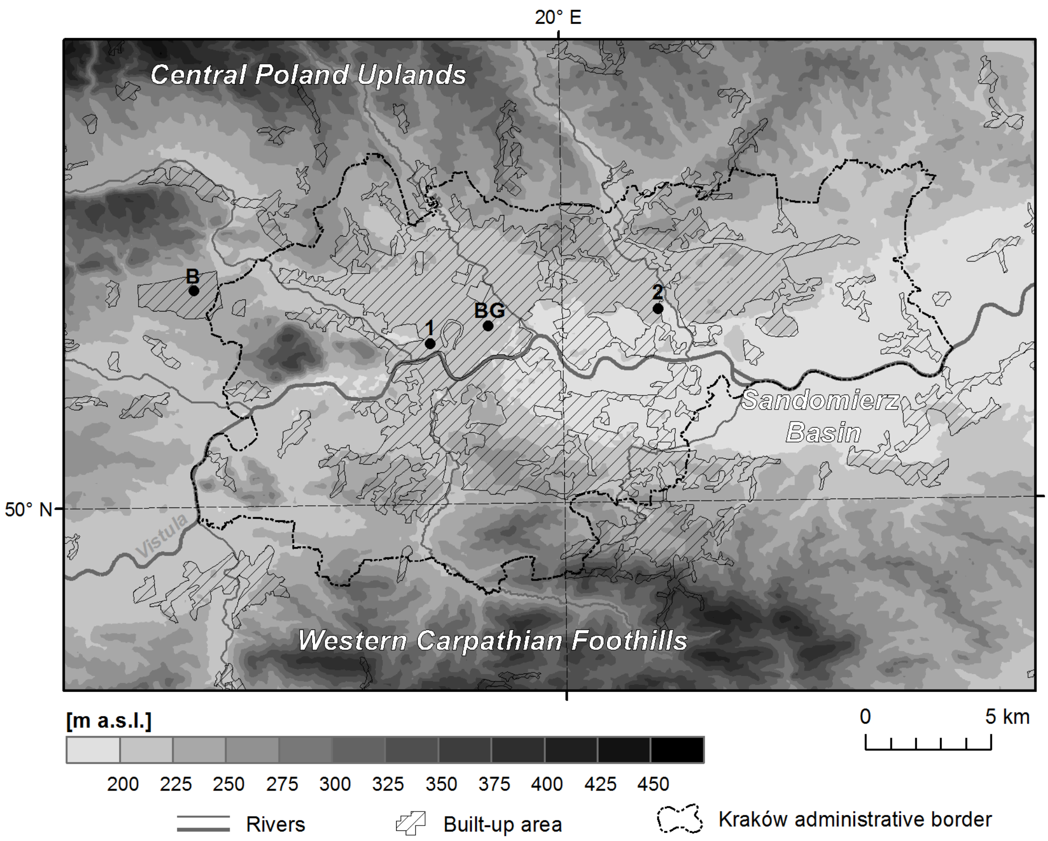

Fig. 1. Study area and the location of the meteorological stations in Botanical Garden (BG) and Balice (B) and air pollution measurement points in the city center: Krasińskiego St. (1) and in Nowa Huta district: Bulwarowa St. (2).

also during the cold half-year due to evaporation from natural surfaces, not covered with streets, buildings etc. In the study period, significant changes in the urban structure, population and air pollution sources (number of vehicles and industrial activity) took place in Kraków. As all those factors contribute to fog occurrence conditions due to e.g., modification of heat balance and condensation nuclei amount, the changes are shortly presented. In the years 1965–1985, large industrial and warehouse investments were realized in the south east part of the city, both in the river valley floor and on the neighboring slopes. In the 1970s and 1980s, large new housing districts with blocks of flats were constructed east of the city center, in the valley floor, as well as on the slopes. The number of inhabitants in Kraków after the Second World War changed mainly due to the territorial expansion of the city. The villages surrounding Kraków were included in the city area (e.g., in 1973 and 1986), which also brought about an increase in the number of inhabitants (from 585 thousand in 1970 to 657 thousand in 1973 and 750 thousand in 1986; Bokwa, 2010). Despite the almost stable number of inhabitants, especially within the latest decades, the number of vehicles registered in Kraków showed a dynamic increase in the study period (Table 1). Moreover, since the change of political and economic system in 1989, Kraków Airport has developed with a significant increase in air traffic, from 100,000 passengers in 1993 to 3.8 million passengers in 2014, including cheap airlines (Bokwa, 2010; Rocznik Statystyczny Krakowa, 2015). The industrial development of the city is also quite a concern. After the Second World War, a huge steelworks and a large new city district were constructed east of Kraków's center and named Nowa Huta. The steelworks began production in 1954. It was designed to produce 1.5 million tons of steel per year but the factory was further developed and in the 1970s production reached 7 million tons per year; at that time, Kraków emitted 17% of the nation's gaseous and 7% of suspended dusts pollution. Later, the industry production was decreasing, first due to the growing inefficiency of the socialist economy and then due to the change of political system in 1989 and the introduction of a market economy (Bokwa, 2010). Steel production in 2015 reached about 1.4 million tons (ArcelorMittal, 2015 and unpublished data). Since 1989, many actions have been undertaken in order to decrease air pollution emissions and improve air quality. The process is still in progress and although Kraków still belongs to the most polluted cities in Europe (European Environment Agency, 2015), positive changes can be clearly seen, e.g., emissions of particulate matter in the Małopolska region decreased by 76% in the period 2004–2014 (Voivodeship Inspectorate of Environmental Protection, 2015).

Table 1. Changes in the number of vehicles registered in Kraków in the study period.

Year	No. of vehicles (in thousands)
1972	52.5
1988	169.1
1998	270.4
2005	383.0
2014	496.0

Data sources: Bokwa (2010); Statistical Office in Kraków (2015).

Studies on fog in Kraków have been conducted so far to show the multiannual variability of the phenomenon (Morawska, 1966, Wypych, 2003) as well as its dependency on atmospheric circulation and preceding weather types (Wiążewski and Bąkowski, 2006, 2007) or atmospheric pollution (Dworak *et al.*, 2000). Fog frequency in Kraków was also the subject of an analysis on horizontal visibility restricting factors by Moskal and Nowosad (2014) or fog's observation methodology by Trepińska and Brus (2006). The authors emphasize the significant decreasing tendency of fog occurrence (Morawska, 1966, Wypych, 2003) with the highest intensity during the latest decades. The probability of a day with fog decreased from 28% in the 1960s to only 7% in the 1990s (10.4 days per 10 years) (Wypych, 2003). Since the correlation between fog occurrence and air pollution in Kraków has been determined as statistically significant at the level of 0.54 (Dworak *et al.*, 2000), the considerable improvement in air quality in the city as well as the distinct increase in saturation deficit (Wypych, 2010) seems to have contributed to the aforementioned fog tendency. Nevertheless fog and mist have remained significant factors influencing horizontal visibility constituting up to 20% of all reducing visibility phenomena (Moskal and Nowosad, 2014) and are still an important problem for air traffic in Kraków (Wiążewski and Bąkowski, 2006, 2007).

DATA AND METHODS

The data used include measurements and observations from the period 1966–2015, from two meteorological stations (Fig. 1):

1. Kraków Botanical Garden (Botanical Garden, BG): the climatological station of the Department of Climatology, Institute of Geography and Spatial Management, Jagiellonian University; the station is located in the Botanical Garden of the Jagiellonian University, in the city center, in the river valley floor (50°04'N, 19°58'E, 206 m a.s.l.); the station belongs to the national meteorological network and the legal name is Kraków Observatory, as it is located in the building which used to be the first astronomical observatory in Kraków. However, at present the building belongs to the Botanical Garden infrastructure as a new observatory is located in the outskirts of the city. Therefore, in order to avoid a misunderstanding, the station is named Botanical Garden in the present paper. The station represents the urban climate of the city center, but the urban impact is mitigated by the influence of the large urban green area surrounding the station;
2. Kraków Balice (Balice, B): the synoptic station in Kraków Airport, administered by the Institute of Meteorology and Water Management – National Research Institute, located in a rural area west of the city, in the river valley floor (50°05'N, 19°48'E, 237 m a.s.l.); in September 2005 the station was slightly shifted within the area of the airport, which is the reason for the lack

of homogeneity in some measurement series.

The following meteorological data and indices were used:

1. Fog observations: available three times per day (06, 12, 18 UTC), together with information about fog intensity (estimated subjectively by the observer, on a scale of 0–2). In parallel, visibility was observed and estimated using the scale 0–9. Fog intensity 0 (thin fogs) is associated with visibility 3 (i.e., 500–1000 m), fog intensity 1 (moderate fog) corresponds to visibility 2 (200–500 m) and fog intensity 2 (dense fog) is linked to visibility 1 or 0 (50–200 m and < 50 m, respectively). The data were used to calculate the annual number of: a. days with fog; a day with fog was defined as a day with at least one fog observation at 6, 12 and/or 18 UTC; b. days with dense fog; a day with dense fog (i.e., intensity 2) was defined as a day with dense fog at least in one of the observation times mentioned; c. days with fog lasting all day long (regardless of the intensity), d. days with fog only at 6 UTC (regardless of the intensity).
2. Wind speed (m s^{-1}): daily measurements available three times per day (06, 12, 18 UTC) for the period 1985–2015. Due to changes in measurement equipment and sensor locations the anemological series cannot cover the whole period of fog observations. Data on wind speed were used to calculate the annual number of: a. days with no wind at any measurement time, b. days with a wind speed of ≤ 2 m s^{-1} at all measurement times and c. days with a wind speed of ≤ 2 m s^{-1} at 6 UTC. According to Morawska (1966), fog in Kraków usually forms during an atmospheric calm or when the wind speed is below 2 m s^{-1} and additionally fog disappearance is often observed when that value is exceeded.
3. Daily minimum air temperature (t_{min}, °C): the difference in t_{min} (K) between the two stations is used as an estimation of maximum UHI magnitude on a certain day. As mentioned above, the shift of the observation site in Balice in 2005 is the cause of the inhomogeneity in air temperature series and therefore UHI magnitude was studied separately for the years 1966–2004 and 2006–2015. Mean annual UHI magnitudes were calculated together with annual numbers of days with large UHI magnitude, i.e., ≥ 2 K.
4. Relative humidity (RH, %): daily measurements available three times per day (06, 12, 18 UTC); as in the case of t_{min}, the data on humidity were studied separately for the periods 1966–2004 and 2006–2015. The indices calculated included the annual number of days with RH $\geq 80\%$ and the annual number of days with RH $\geq 95\%$, with the thresholds exceeded at any measurement time. The criterion RH $\geq 80\%$ corresponds to the results presented by Klemm and Lin (2016) while the criterion RH $\geq 95\%$ groups cases with high potential for fog formation, especially on days with high air pollution (e.g., Menut *et al.*, 2014).

Another element taken into account was the atmospheric circulation. For each day of the study period, information about the synoptic situation type was obtained from the calendar of circulation types for the territory of Southern Poland by Niedźwiedź (1981, available at: http://klimat.wnoz.us.edu.pl/#!/glowna, extended by the Author, 2016). It is based on air mass advection and type of pressure system (c – cyclonic; or a – anticyclonic), taking into account also non-advective situations (Ca – high center; and Ka – anticyclonic wedge or ridge of high pressure; as well as Cc – center of low pressure; and Bc – trough of low pressure). A detailed description of all the classification schemes can be found in the cited literature (Niedźwiedź 1981, 2000, 2016). For each year, the seasonal number of cases of each type was calculated and then the frequency of particular types in the study period was obtained.

Air pollution is considered as mean annual concentration (µg m^{-3}) of total suspended particulates (TSP) or PM_{10}, NO_x and SO_2. As the measurement methods and organization were changing during the study period (Bokwa, 2008), the data had to be divided into two parts:

- for the period 1968–2001: data on TSP and SO_2 available only as mean areal concentrations for the districts City Center and Nowa Huta (Bokwa, 2008), both located in the valley floor similar to both stations considered;
- for the period 1993–2015: automatic measurement data of PM_{10}, NO_x and SO_2 from two points representing the city center (Krasinskiego St.) and Nowa Huta district (Bulwarowa St.) (Fig. 1), operated by the Regional Inspectorate for Environmental Protection (http://monitoring.krakow.pios.gov.pl).

For each index and station, the data series for 1966–2015 or for the sub-periods mentioned were standardized following the formula:

$$z = \frac{x - \mu}{\sigma} \quad (1)$$

where:
x - non-standardized value, µ - mean value, σ - standard deviation.

For each series, the linear trend was established together with statistical significance. Results at $p < 0.01$ were considered to be statistically significant. The relations between multi-annual changes in days with fog and other elements were studied with the correlation coefficient. Values ≥ 0.5 and statistically significant ($p < 0.01$) were considered important for the explanation of factors which control fog occurrence in Kraków.

RESULTS AND DISCUSSION

Changes in Fog Frequency

In the period 1966–2015, there were 2298 days with fog in the study area (i.e., fog was observed at least at one of the stations, and at least during one observation time: 06, 12, 18 UTC) which makes 12.6% of the whole period. The total number of days with fog can be further divided as follows:

a. days with fog at both stations (Balice and Botanical Garden): 42.0%;
b. days with fog only at Balice: 17.6%;
c. days with fog only at Botanical Garden: 40.4%.

Over 80% of days with fog occurred in the cold half-year (Oct.–Mar.), and from that amount over 60% at 06 UTC only. In spite of the higher mean annual number of days with fog at Botanical Garden (37.9 days) than at Balice (27.4 days), the mean annual number of days with dense fog was higher at Balice, 9.4 days, than at Botanical Garden, 7.5 days. Witiw and LaDochy (2008) explained such a pattern with the difference in night air temperature inversion magnitude and its vertical extent between rural and urban areas. Fog lasting all day long occurs in the study area only during the cold half-year and it is a rare phenomenon (1.4 days per year in Balice and 3.2 days in Botanical Garden, on average). Fig. 2 (see also the Annex) shows changes in the annual number of particular types of days with fog in the study period. In all cases, statistically significant decreasing trends are observed. The year 1987 seems to be a turning point; for the earlier period, the standardized values are positive, while later, negative ones prevail. The detailed analysis of the long term tendency has been performed independently for Botanical Garden and Balice stations using the 20-year moving window linear trend. Until 1987, the urban station was distinguished by a significant decrease in fog days, whereas the rural location represented multiannual variability within the first decade and the decline started not before 1975, and was considerably less significant. Since the turning point of 1987, the tendency has lost its magnitude or even significance and at Balice a slight increase in the annual number of fog days can be observed.

As mentioned above, about 60% of days with fog were observed at only one of the two stations considered. Fig. 3 shows that in the case of days with fog, fog all day long and fog at 06 UTC only, observed at both stations and at Botanical Garden only, there is a clear and statistically significant decreasing tendency (see also Annex), similar to those shown in Fig. 2. Only in the case of days with dense fog, significant decreasing trends were found for both stations and for Balice only, while the decreasing trend for the Botanical Garden only option was insignificant. That clear difference between urban and rural stations shows the high importance of local-scale factors controlling fog occurrence in the study area, while the clear decreasing tendency of fog observed at both stations can be linked to regional and macro-scale effects. That feature is further analyzed below for factors potentially controlling fog frequency.

The observed long-term decreasing trends presented above are in accordance with the findings concerning Europe (van Oldenborgh *et al.*, 2010) and many other regions in the world (Klemm and Lin, 2016). Also in Poland, the decreasing trend of about 8–10 days per decade has dominated, especially at stations located in cities. However, the number of days with fog has increased slightly in rural sites, in particular in the mountain areas where the most dominant factor is an increasing amount of water vapor in the atmosphere. Unfortunately, the research has not been widely conducted due to the subjectivity of fog observations and data inhomogeneity (Lorenc and Myszura, 2012). The decreasing tendency of fog occurrence in urban areas has been explained by the decline in particulate matter concentration (Wypych, 2003, Lorenc and Myszura, 2012).

Role of Particular Factors in Fog Frequency Control

Atmospheric circulation is one of the most important factors influencing the occurrence of weather phenomena. It has also been defined as crucial in the case of fog occurrence in Kraków (Wypych, 2003, Wiążewski and Bąkowski 2007). Regardless of the station location (urban or suburban area) the conditions favorable for fog occurrence include, among other elements, non-advective synoptic situations (Ca, Ka, Bc and Cc) and cyclonic or anticyclonic situations with advection from SE to SW. For example, in 2014 the number of days with fog was much higher (Balice: 31 days, Botanical Garden: 28 days) than in any other year of the period 2006–2015 (on average about 20 days per year at Balice and 17 days at Botanical Garden). In the same year, the frequencies of circulation types SEa and SEc were the highest in that 10-year period; advection from SE usually brings to Kraków warm and humid air masses from the Black Sea region, which enhances fog formation (Wiążewski and Bąkowski 2007).

Since the role of atmospheric circulation in fog formation is unquestionable, but the multiannual variability of both elements has not yet been described, series of the number of days with particular fog characteristics and the number of days with fog favoring or fog limiting circulation types during the period 1966–2015 were correlated. Regarding seasonal effects of atmospheric circulation intensity, the analyses were performed separately for the warm (Apr.–Sep.) and cold (Oct.–Mar.) half-year. Moreover, as mentioned above, fog occurrence is much more frequent during the cold half-year, therefore, that season has been mostly taken into consideration (Fig. 4).

In the analyzed period no significant tendency in atmospheric circulation intensity was confirmed. The main circulation indices (Niedźwiedź, 2000) – the zonal (westerly) index and meridional (southerly) index, calculated for both seasons – demonstrate statistically insignificant variability, whereas a slight increasing trend can be observed in the frequency of anticyclonic circulation types, especially in the cold half-year. In spite of that increase, fog favoring types (Sa, SWa, Ca, Ka) show no significant tendency and no significant correlation with long-term fog occurrence frequency. Furthermore, a slight decrease in the number of days with fog limiting types has been recorded during the cold half-year, which makes the circulation dependency of fog occurrence in Kraków even more complex.

The second fog favoring factor defined is relative humidity. The studies on its long-term variability in Kraków have revealed a considerable decrease especially in spring, but statistically significant also in other seasons (Wypych, 2010). The annual number of days with RH $\geq$ 80% and RH $\geq$ 95% in the period 1966–2004, at each station, showed a decreasing trend, statistically significant (Fig. 5, Annex). In the case of Botanical Garden, all correlation coefficients showing the relation between days with RH $\geq$ 95% and particular types of days with fog occurrence exceeded the value 0.5 and were statistically significant. The same applies to days with RH $\geq$ 80%, except days with dense fog. However, in

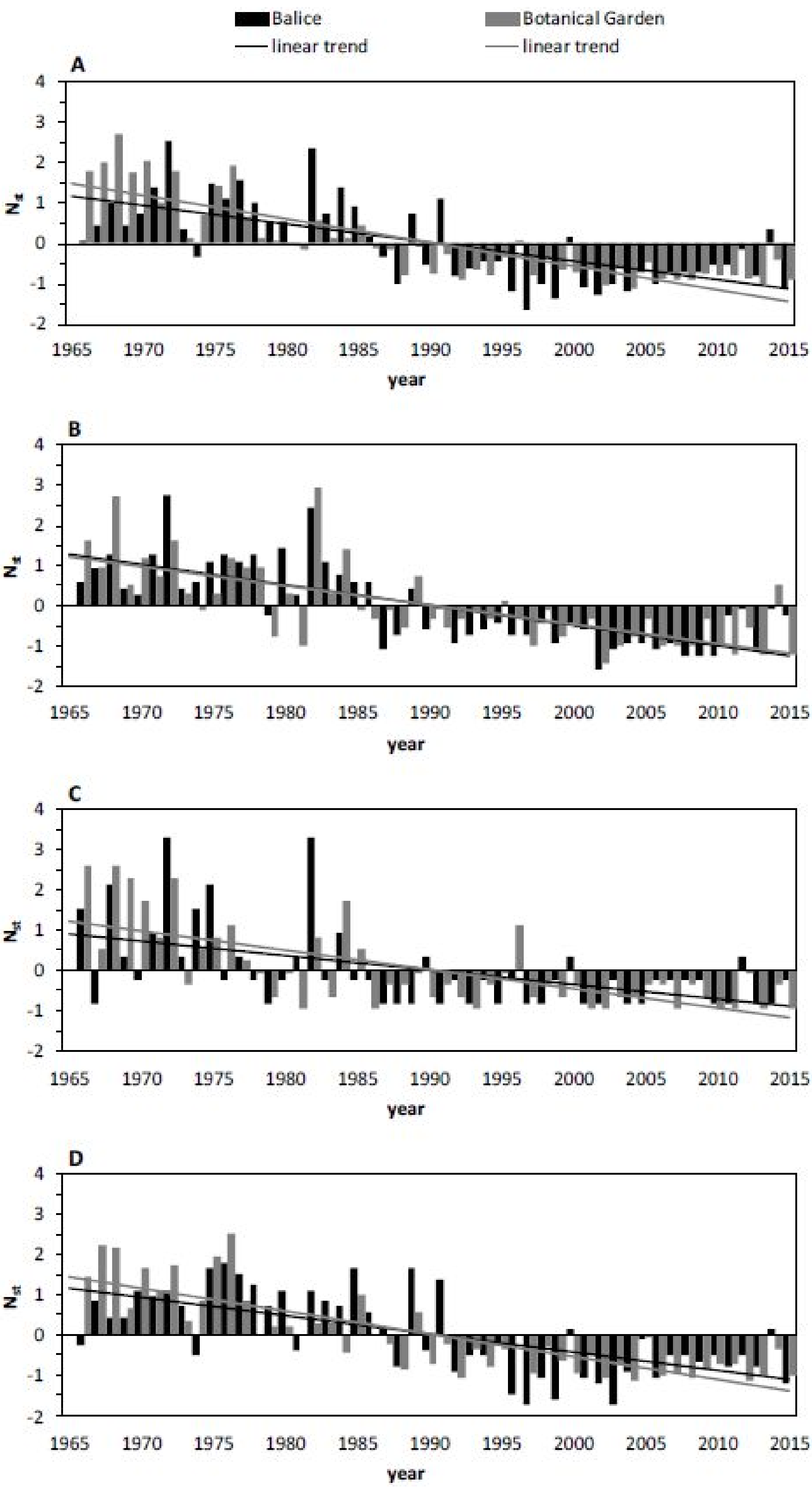

Fig. 2. Standardized series of the annual number of days with: fog (A), dense fog (B), fog lasting all day long (C) and fog observed only at 06 UTC (D), at the stations Balice and Botanical Garden in the years 1966–2015.

the case of Balice, only in two cases can the correlation be regarded as significant: for days with RH ≥ 95% and days with dense fog and days with fog lasting all day long. In the period 2006–2015, none of the series considered showed any statistically significant trend and none of the correlation coefficients exceeded 0.5 or was statistically significant.

Therefore, in order to further study the potential relationships between the two elements, for both stations, fog frequency was calculated also for RH values in the following intervals: ≤ 80%, 81–85%, 86–90%, 91–95% and 96–100%. All fog observations from all measurement times were included and the results are as follows:

A. Botanical Garden: 2.7, 2.8, 9.1, 25.7 and 59.7%.

B. Balice: 0.5, 1.0, 3.6, 13.0 and 81.8%.

In Botanical Garden, only about 60% of fog cases were accompanied by RH 96–100% while in Balice it was almost 82%. This confirms the earlier findings showing that fog in urban areas can form at rather low RH values (e.g., Menut *et al.*, 2014; Klemm and Lin, 2016) and also explains why in the case of Balice and the period 1966–2004, only the correlation with days with RH ≥ 95% was significant.

As mentioned before the location of the city in a river valley significantly influences the anemological conditions, which are among the most important factors in fog formation (Sachweh and Koepke, 1997). In the period 1985–2015 (available for wind velocity data), annual numbers of days with wind speed ≤ 2 m s^{-1} at 06 UTC, wind speed ≤ 2 m s^{-1} at all measurement times and atmospheric calm at all times showed statistically significant decreasing trends at both stations (Fig. 6, Annex). This is also the period confirming the lower frequency of fog days (Fig. 2). For the same period (i.e., 1985–2015), the annual numbers of days with fog have a statistically significant downward trend only in three cases (out of eight series of days with fog considered). That is due to the fact that around 1986–1987 there is a turning point in fog frequency, as can be seen in Fig. 2. That is also the reason why none of the correlation coefficients for all options of days with fog and days with a particular

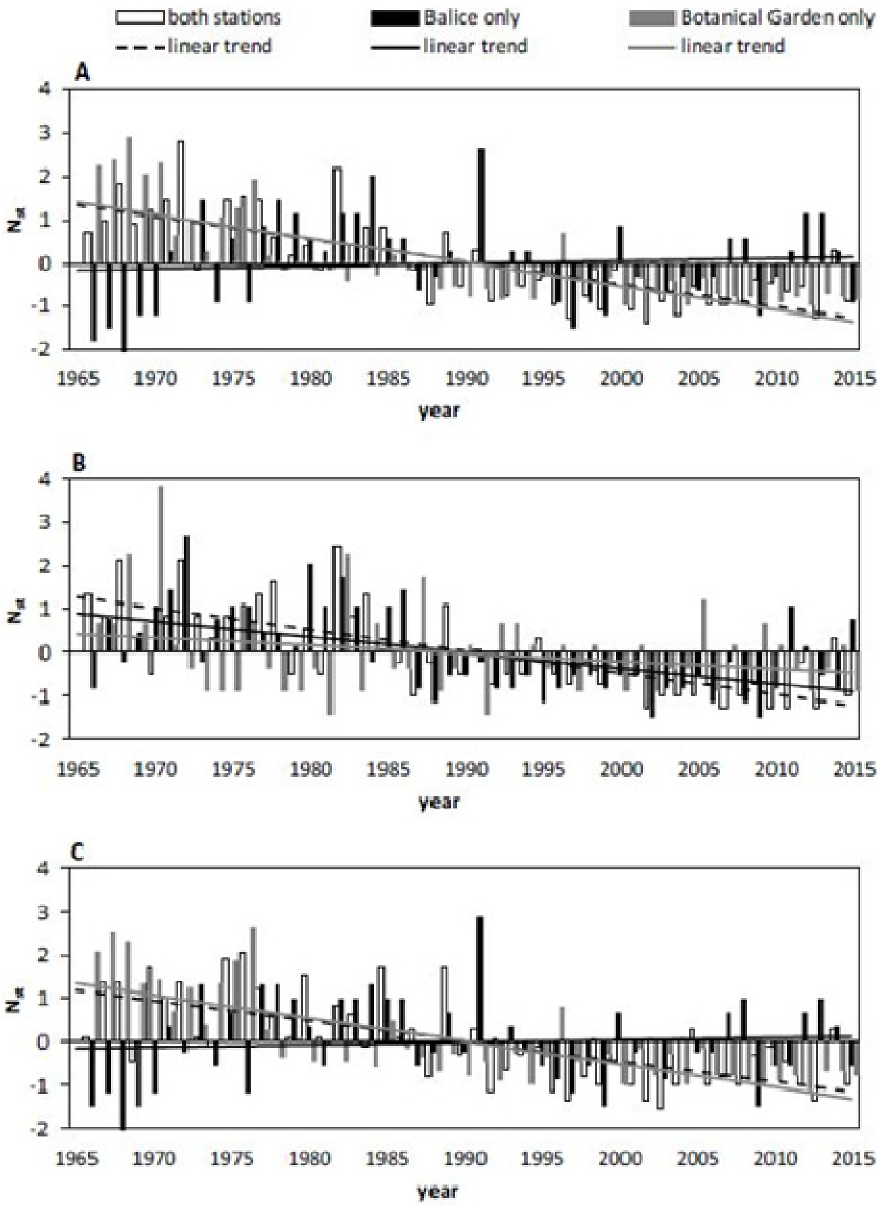

Fig. 3. Standardized series of the annual number of days with: fog (A), dense fog (B) and fog observed only at 06 UTC (C) which were observed at both stations or only at one station in the years 1966–2015.

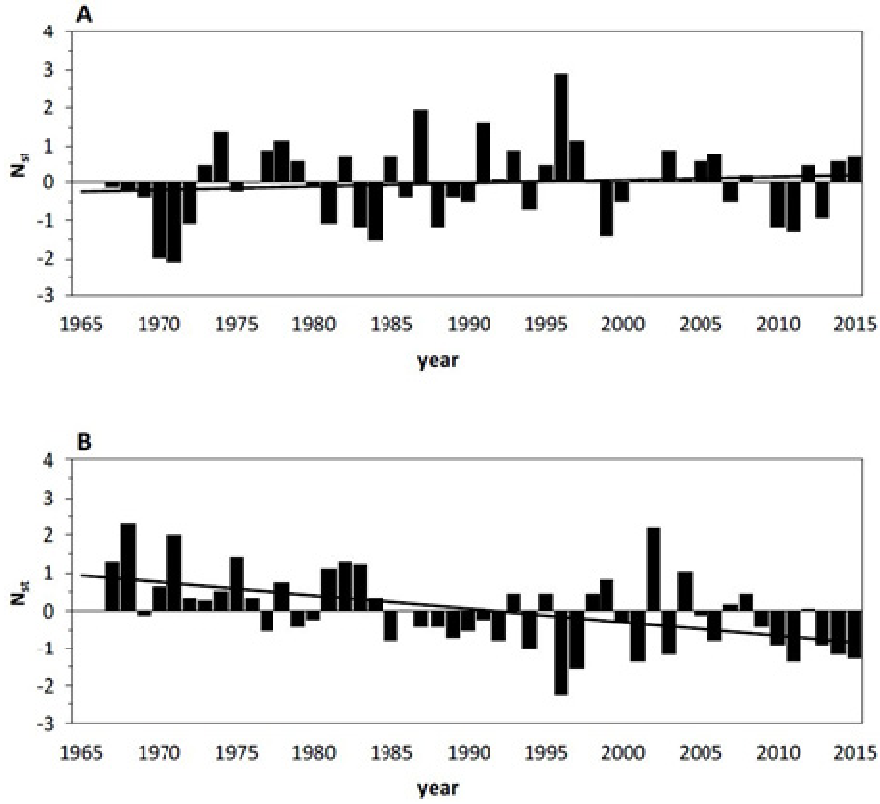

Fig. 4. Standardized series of the annual number of days with circulation types favoring fog occurrence (A) and limiting fog occurrence (B) in the cold half-year of the period 1966–2015.

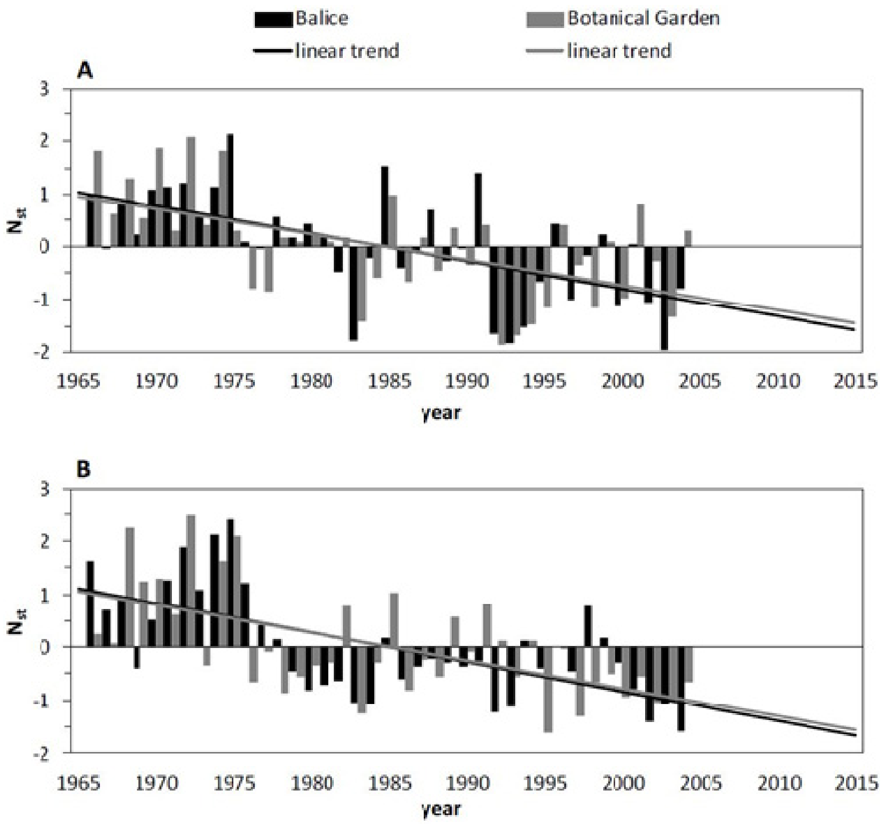

Fig. 5. Standardized series of the annual number of days with RH ≥ 80% (A) and RH ≥ 95% (B) noted at least at one measurement time at the stations Balice and Botanical Garden in the period 1966–2004.

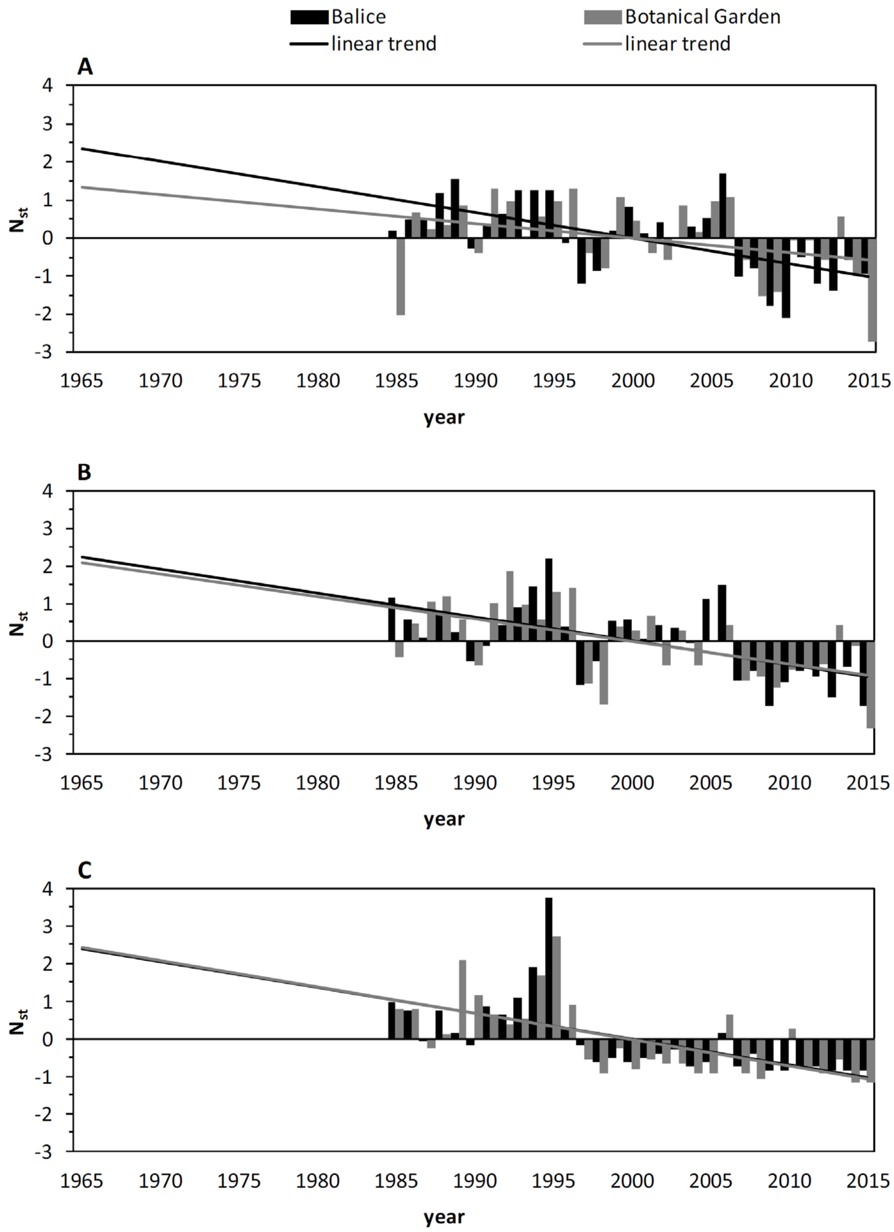

Fig. 6. Standardized series of the annual number of days with: wind speed ≤ 2 m s^{-1} at 06 UTC (A), wind speed ≤ 2 m s^{-1} at all measurement times (B) and atmospheric calm at all times (C) at the stations Balice and Botanical Garden in the years 1985–2015.

wind speed exceeded 0.5 and only one value was statistically significant. Nevertheless, a clear decreasing trend of days with low wind speeds can be regarded as a factor contributing to the decrease in fog occurrence.

Minimum air temperature, UHI magnitude and number of UHI magnitude cases ≥ 2 K were analyzed separately for the periods 1966–2004 and 2006–2015, due to changes at Balice station as mentioned above. Both stations represent the lowest part of the study area, where UHI is much more intense than in higher areas (Bokwa *et al.*, 2015). No significant trend in mean annual and mean seasonal UHI magnitudes or extreme UHI cases were found for the period 1966–2004 and at both stations mean annual t_{min} showed a statistically significant increase at the same rate of 0.3°C per 10 years. Like in the case of atmospheric circulation, no change in the tendency of standardized values occurred around 1987, a turning point in fog frequency series. Each series of the annual number of particular days with fog was correlated with the annual UHI magnitude and UHI extreme cases and the correlation coefficient has not exceeded 0.5 in any case. Values that are statistically significant are shown in Table 2.

In the years 2006–2015, mean annual UHI magnitude and the number of extreme UHI cases showed a statistically significant decrease; as for mean annual and seasonal t_{min} at Botanical Garden no tendency could be found, but in the case of Balice a significant increase was noted. Only for days with dense fog at Balice did the correlation coefficient

Table 2. Correlation coefficients for annual number of particular days with fog and mean annual UHI magnitude and annual number of days with UHI magnitude ≥ 2 K in the years 1966–2004.

	Fog		Dense fog		Fog all day long		Fog only at 6 UTC	
	B	BG	B	BG	B	BG	B	BG
Mean UHI	0.31	0.12	0.28	0.28	0.00	0.11	**0.39**	0.20
UHI ≥ 2 K	**0.34**	0.22	**0.32**	**0.32**	0.02	0.20	**0.41**	0.26

Explanations: B – Balice, BG – Botanical Garden, in bold: statistically significant values.

reach –0.55 in the case of mean annual UHI and –0.52 in the case of extreme UHI cases, but none of the values obtained was statistically significant. Therefore, it can be concluded that fog occurrence in Kraków and its environs was not significantly affected by UHI; as for the part of the city located in the valley floor, UHI has not shown significant changes in the period 1966–2004 when large changes in fog occurrence were observed.

Data concerning air pollution and days with fog were analyzed separately for the periods 1968–2001 and 1993–2015, due to data available. In the first sub-period, for both kinds of air pollution (i.e., TSP and SO_2) strong decreasing trends, statistically significant, were observed for both districts (i.e., City Center and Nowa Huta). Strong correlation between air pollution with TSP and all kinds of days with fog can be observed, i.e., the correlation coefficients reach 0.7–0.8 and all values are statistically significant (Table 3). Concerning SO_2, the concentrations measured in the city center were more important for fog occurrence than the concentrations measured at Nowa Huta. The reason is that SO_2 concentrations in Nowa Huta increased significantly in mid-1970 due to an increase in production at the steelworks, as mentioned above. In the case of air pollution, the year 1988 seems to be a turning point in the series of standardized values (Fig. 7), which is very close to 1987 as a turning point in the case of the data for fog. That can be regarded as another indicator of the strong links between fog occurrence and air pollution level changes. As the impact of air pollution on fog occurrence is much more significant than the impact of other elements discussed, the turning point of 1987–1988 seems worth a short comment. Emissions of particulate matter from industrial sources began to decrease significantly in early 1990s, i.e., a few years after the turning point. But in 1985, a power plant located in the town of Skawina, west of Kraków, was included in the Kraków's heating system (Heat for Kraków, 2017), and in 1986, in the power plant "Łęg" located within Kraków area, a new unit was completed (Elektrocieplownia Krakow, 2016). Therefore, many small local individual heating installations were closed and replaced by the central heating delivery.

The changes took place gradually and could contribute to the drop of local air pollution and the drop of the number of days with fog in the two measurement points included in the study already in 1987, but the contribution to the areal mean annual particulate matter concentrations decrease was probably visible one year later.

In the case of the period 1993–2015, none of the correlation coefficients exceeded 0.5 or was statistically significant. Trends in air pollution changes were not statistically significant, except a decreasing one for SO_2. Klemm and Lin (2016) concluded that changes in fog frequency are dependent mainly on changes in concentration of precursor gases for the formation of small, hygroscopic particles, mainly SO_2 and NO_x, as PM_{10} and $PM_{2.5}$ are not effective reducers of visibility when relative humidity increases. The data for Kraków for the period 1968–2001 support these findings, but the data for 1993–2015 rather show no connection between fog frequency and air pollution. It might be due to the fact that while PM_{10} concentrations have consistently exceeded the permitted values, SO_2 concentrations have remained far below these levels and therefore other factors became decisive. On the other hand, high concentrations of PM_{10} can contribute to the decrease in fog frequency as the particles absorb surface long-wave radiation during night (coming from the earth surface), thereby reducing radiative cooling at night and promoting conditions which are less favorable for fog production (Li *et al.*, 2012). Witiw and LaDochy (2008) argued that the decrease in dense fog in Los Angeles was due to the decrease in TSP. In the case of Kraków, we can see a strong relation between these two elements. However, taking into consideration the fact that the study for LA dealt with dense fog cases, it has to be stressed that the number of days with dense fog was on average higher at Balice than at Botanical Garden. There are no air pollution measurements at Balice but it can be assumed that TSP or PM_{10} concentrations were much lower there than in the city center, where there are numerous old heating facilities. They contribute to emissions

Table 3. Correlation coefficients for mean annual concentrations of SO_2 and TSP, in the city center and in the district Nowa Huta, and annual number of particular days with fog in the years 1968–2001.

Pollutant	Area	Fog		Dense fog		Fog all day long		Fog only at 6 UTC	
		B	BG	B	BG	B	BG	B	BG
SO_2	Center	**0.64**	**0.53**	**0.58**	0.36	0.32	0.31	**0.72**	**0.56**
	N. Huta	0.37	0.09	0.24	0.07	–0.10	–0.09	**0.55**	0.18
TSP	Center	**0.70**	**0.82**	**0.72**	**0.56**	**0.57**	**0.64**	**0.65**	**0.80**
	N. Huta	**0.75**	**0.79**	**0.74**	**0.64**	**0.56**	**0.63**	**0.70**	**0.77**

Explanations as in Table 1.

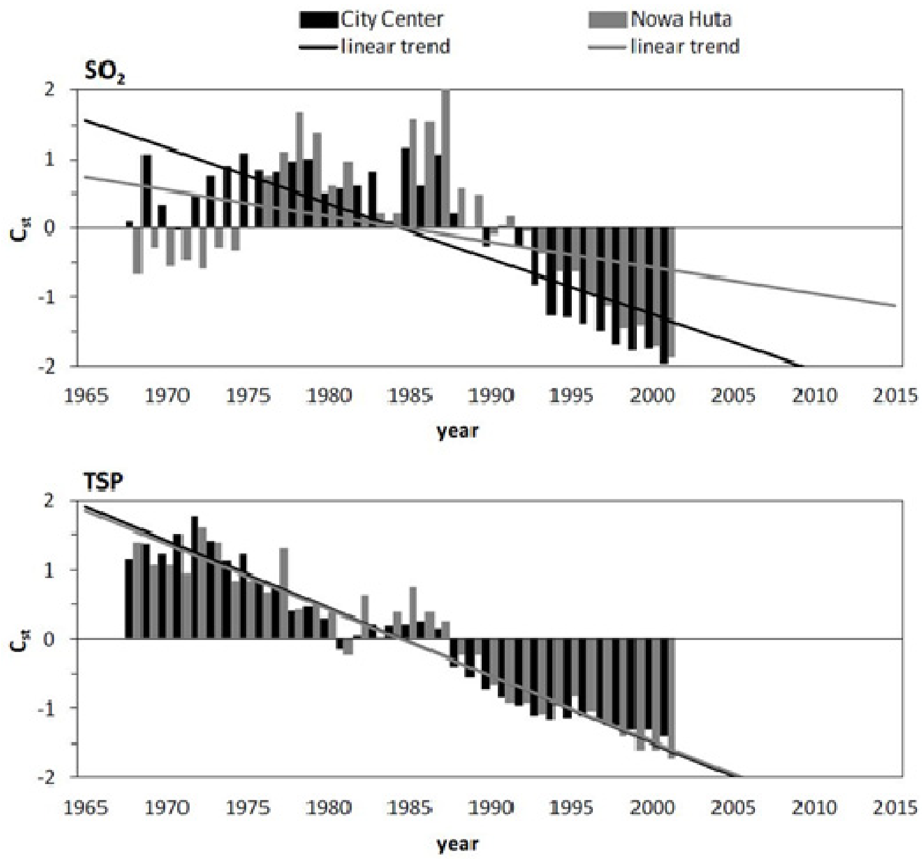

Fig. 7. Standardized series of the mean annual concentrations of SO_2 and TSP in the districts of Kraków: City Center and Nowa Huta in the years 1968–2001.

in the urban canopy layer and often become trapped in the inversion layer, which leads to a rapid increase in pollution concentration above the permitted levels.

CONCLUSIONS

The analyses presented above show that the large decrease in fog frequency, observed in the central part of Kraków and its western suburbs located in the valley floor in the period 1966–2015 (by about 70% at Botanical Garden and 50% at Balice, respectively), was connected mainly with changes in air pollution (decrease in SO_2 concentrations by about 80% and in TSP by about 70%). Despite the fact that no significant role of circulation variability in the reduction of the number of days with fog in Kraków was defined, it must be emphasized that anemological and hygric conditions representing circulation impact are significantly modified by local environmental conditions, such as the relief and drainage systems.

From the two anthropogenic factors analyzed, UHI showed no significant impact on fog frequency, as UHI magnitude for the part of the city and its environs located in the valley floor (where both meteorological stations considered are located) showed no significant changes. New urban structures were constructed during the study period in areas elevated several tens of meters above the valley floor and the relief of Kraków is an equally important factor as the land use/land cover in urban climate modification; therefore, we are dealing with RMUHI (Relief Modified Urban Heat Island) (Bokwa *et al.*, 2015). However, as mentioned above, the second anthropogenic factor, i.e., air pollution, turned out to have the largest contribution to fog occurrence. Shi *et al*. (2008), using data for China, showed that the impact of a city on fog formation depends on the stage of the city's development. In Europe, we can also observe similar significant changes during the last few decades, but the sequence is reversed; cities which became strong industrial centers after the Second World War, later changed the function and air pollution decreased. For example, in Essen, Germany, air pollution, especially concerning SO_2, decreased from about 60 µg m^{-3} in the early 1980s to less than 10 µg m^{-3} in 2012 (mean annual concentrations), in connection with the closing of the coal mines operating in the region and structural changes in the industry. The annual number of fog days showed a strong decreasing trend during the same period from about 70 to 20 days and was explained as a result of the decrease in air pollution (Kuttler *et al*., 2015). The results for Kraków presented above are another example of that pattern. It is worth mentioning that during the high air pollution period, the number of days with fog was much higher in the city center than at the rural station, while at present it is much lower at both stations and slightly higher at Balice than at Botanical Garden station.

Data for the last part of the study period (2006–2015) allow us to define the present state of fog conditions in Kraków and to formulate predictions for the future. Unlike in the 1960s and 1970s, annual numbers of days with fog are very similar at both stations. However, as the air pollution is much lower than in the 1960s and 1970s, atmospheric circulation seems to be the key factor controlling the fog frequency at present; its impact is intensified by local environmental factors, mostly the relief. Even though fog frequency in Kraków shows no significant trend during last 20 years and the mean annual number of days with fog remains relatively low, the phenomenon should be studied further in the context of future climate change, as fog occurrence is a natural hazard, potentially dangerous mainly for the transportation sector.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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