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Role of Fog in Urban Heat Island Modification in Kraków, Poland

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ABSTRACT

The impact of fog on relief modified urban heat island (RMUHI) in Kraków has been presented using fog observations at 06 UTC from two meteorological stations: a rural one (Balice, B) and an urban one (Botanical Garden, BG) from the period 2006–2015. Daily UHI magnitude for the valley floor for the same period was estimated as $T_{min}BG–T_{min}B$, while for the period 2010–2015, eight daily courses of UHI were available, for the urban areas in the valley floor and 50 m above it, together with air temperature inversion data. UHI data for days with various combinations of fog occurrence and weather conditions were compared using non-parametric statistical tests: Wald-Wolfowitz test, Kolmogorov-Smirnov test and U Mann-Whitney test. Data of 2010–2015 were also the subject of cluster analysis (k-means method). Fog is an important factor decreasing UHI magnitude by about 1 K but mainly during weather conditions with little or no cloudiness and small wind speed or atmospheric calm, during anticyclonic synoptic situations, and only in the valley floor areas. With an increase in cloudiness and wind speed, the role of fog decreases and is similar in all parts of the city.

Keywords: Fog; Relief modified urban heat island; Atmospheric circulation; Cluster analysis.

INTRODUCTION

Urban heat island (UHI) is probably both the clearest and the best documented example of inadvertent climate modification. The difference between air temperature at screen level in urban area and in surrounding rural area defines UHI magnitude or intensity (Oke, 1987). The interactions between fog and UHI are usually discussed in the context of the impact of increased air temperature in urbanized areas on potential conditions for fog formation (e.g., Sachweh and Koepke, 1995, 1997; LaDochy, 2005; Shi *et al.*, 2008; Witiw and LaDochy, 2008; Li *et al.*, 2012). The impact of fog on UHI, reported in most studies, is latent heat release during fog formation, which leads to an increase in minimum air temperature (e.g., Gough and He, 2015; Tam *et al.*, 2015). High air pollution with particulate matter is connected not only with the abundance of fog condensation nuclei but also with the absorption of surface long-wave radiation, which diminishes radiative cooling at the surface and raises minimum air temperature, too (Li *et al.*, 2012; Gough and He, 2015). UHI in Kraków, Poland, is a part of a complicated air temperature spatial pattern which is controlled by both land use/land cover and relief; therefore, the concept of RMUHI (Relief Modified Urban Heat Island) needs to be used (Bokwa *et al.*, 2015). Additionally, the city experienced large changes in both fog frequency and the factors important for fog occurrence after the Second World War (Bokwa *et al.*, 2018).

Although fog is often formed during similar weather conditions when the highest UHI magnitude values are observed, i.e., during windless nights or nights with low wind speed, local environments are also of a high importance influencing turbulence and radiative processes (Gultepe *et al.*, 2007). Cloudiness is the second most important factor that controls UHI magnitude, so it should be taken into consideration in parallel. During the nights with low wind speed and little cloudiness, rural areas surrounding Kraków, due to the location in the area with diversified relief, experience katabatic flows and cold air reservoir formation, which favors fog formation, while the urban areas' impact is the opposite. Therefore, it can be expected that the UHI magnitudes for clear nights might be significantly modified by fog occurrence.

The aim of the study is to estimate the effect of fog occurrence in Kraków on UHI magnitude and its night-time course, taking into account the difference caused by the relief. The influence is examined during different weather conditions in two vertical urban zones described: the valley bottom and the areas located 50 m above.

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DATA AND METHODS

Kraków is located in the Vistula River valley surrounded by the Wieliczka Foothills to the south and the Kraków Upland to the north. The highest points of both regions reach about 200–250 meters above the bottom of the valley, but hilltops closest to the valley are located about 100 m above the valley floor. Diversified relief within the city area and the hydrography result in the modification of many climate features. An important role is also played by urban and industrial land use. The rapid development of industry after the Second World War caused dynamic spreading of the city. Because of the city's location and intensive human activity, the bioclimate of Kraków is considered to be rather unfavorable for the inhabitants (the study area has been described in detail in Bokwa *et al.*, 2018).

UHI magnitude (in Kelvins) is the air temperature difference between an urban and a rural measurement point. Analysis of fog's impact on UHI magnitude has been conducted for the period 2006–2015 using data from two measuring points only, located in the city center (Botanical Garden) and in the suburbs (Balice), and for a shorter period 2010–2015 with data from the network of over a dozen sensors placed across the city area (Fig. 1). Until 2010, long-term UHI magnitude's variability in Kraków could be studied using only the two stations mentioned, due to lack of other measurement data needed. Unfortunately, in 2005 the location of the station in Balice was slightly shifted and the homogeneity of the air temperature measurements was lost. Therefore, only the period 2006–2015 is used in the present paper to obtain long-term information on UHI magnitude and fog, as a background for the analyses for the shorter period of 2010–2015, for which the information on UHI magnitude is much more complete.

For the first period under consideration (i.e., 2006–2015), daily values of minimum air temperature were used to estimate UHI magnitude and they come from the following: 1. synoptic station in Kraków-Balice Airport (further named Balice or B), 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.), administered by the Institute of Meteorology and Water Management – National Research Institute, and 2. climatological station of the Department of Climatology, Institute of Geography and Spatial Management, Jagiellonian University, located in the city center and in the river valley floor (50°04'N, 19°58'E, 206 m a.s.l.), in the Botanical Garden of the Jagiellonian University (further: Botanical Garden or BG). The magnitude of UHI (in Kelvins) was calculated as a simple difference between the city center (T_{min}BG) and the suburbs (T_{min}B). Data on fogs come from the observations taken at both stations a three times per day (06, 12, 18 UTC), including also information about fog intensity estimated from visibility data measured by expert observers (both stations) and instrumentation (Balice station).

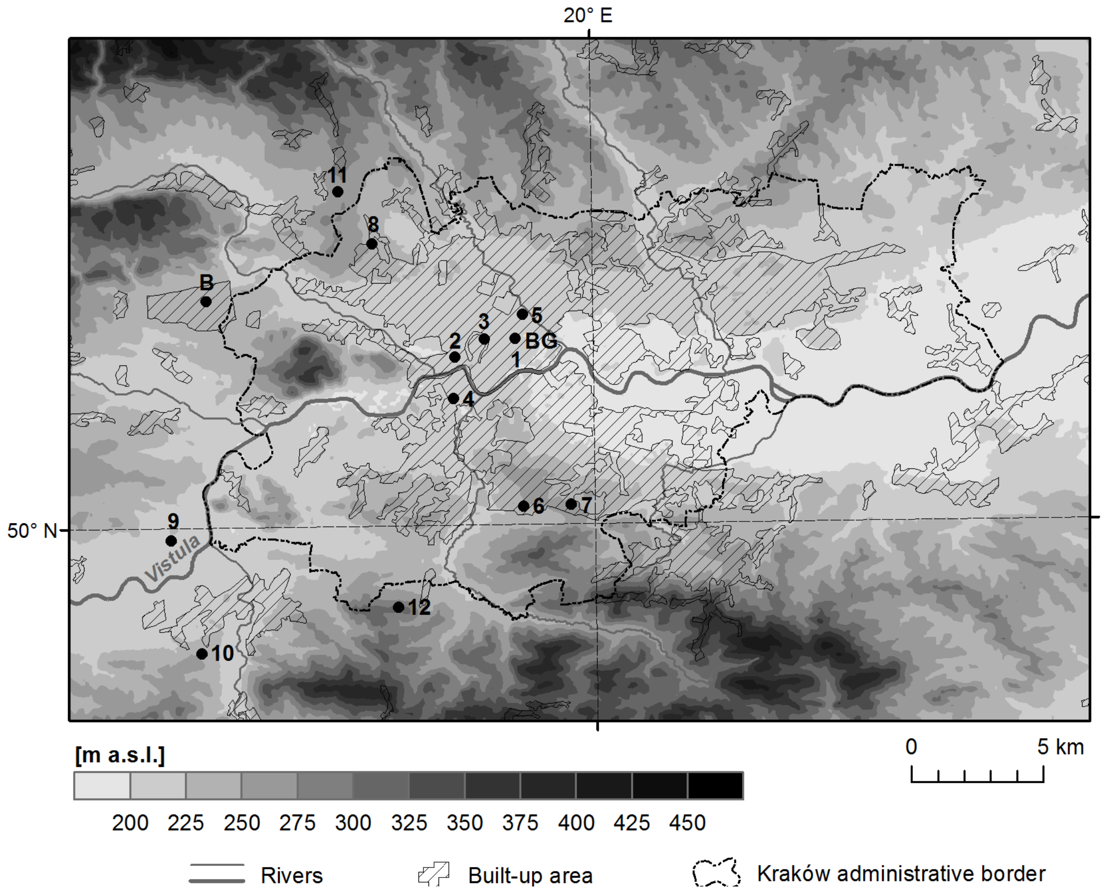

Fig. 1. Relief and land use of the study area and the location of measurement points.

All events when the phenomenon reduces horizontal visibility below 1 km are defined as thin fogs (fog intensity 0), moderate fog limits the visibility to 500 meters (fog intensity 1), whereas dense fog corresponds to the visibility < 200 meters (fog intensity 2). Additional meteorological data – wind speed (WS) and cloudiness (N) – were also taken into consideration to distinguish conditions favorable for high UHI magnitudes, defined by WS ≤ 2 m s^{-1} (atmospheric calm or weak wind) and N ≤ 2/8 (clear sky or little cloudiness) when outgoing longwave radiation fluxes are usually the largest (further named radiative weather type, RWT, in contrast to other cases: NRWT). The data on wind speed and cloudiness were available every 3 hours at Balice and three times per day (06, 12, 18 UTC) at Botanical Garden.

The analyses were conducted for the cold half-year only (Oct.–Mar.), as it is a season more prone to fog occurrence (80% of all fog days) (Bokwa *et al.*, 2018). A day with fog was defined as a day when the phenomenon occurred at least at one of the stations, and at least at one of the observation times (i.e., 06, 12, 18 UTC). Since 67% of fog days (i.e., 152) were those with fog noted at 06 UTC only, further analyses were limited to those cases solely. As a first step, nights with radiative weather type (RWT) (i.e., WS ≤ 2 m s^{-1} and N ≤ 2/8 at Balice at 03 and 06 UTC and at Botanical Garden at 06 UTC on a day with fog at 06 UTC) and non-radiative weather type (NRWT, other cases) were distinguished and further analyses were conducted separately for both groups of nights. Within each group, for nights with fog at 06 UTC at one or both stations and for nights without fog, UHI magnitude was calculated.

As for 2006–2015 only one value per night concerning UHI magnitude was available, the procedure for estimating the effect of fog on UHI was based on the sequences of UHI magnitude value frequencies in 0.5 K intervals for the selected groups of nights. The 10-element series obtained were compared using nonparametric tests: Wald-Wolfowitz test, Kolmogorov-Smirnov test and U Mann-Whitney test, due to the small sample size and unknown distribution (StatSoft, 2006).

For the period 2010–2015, the same procedure was used concerning data on fog, wind speed and cloudiness. However, temperature data for the second period were obtained from a measurement network established in the area of Kraków and its vicinity (Bokwa *et al.*, 2015). The network consists of 21 measurement points and in the present paper data from only 12 points, located in the western part of the city, were used (Fig. 1). This choice is linked to the fact that the station in Balice is located west of the city borders, i.e., within the same part of the city as the automatic measurement points. The points chosen represent three main vertical zones of the city and its surroundings and the main types of land use/land cover to be found in particular zones:

- urban green areas, city center, valley floor (Botanical Garden, No. 1).
- urban canyon, city centre, valley floor (Krasińskiego St., No. 2).
- old town compact built-up area, city centre, valley floor (Slowackiego Theatre, No. 3).
- area with blocks of flats, valley floor (Podwawelskie district, No. 4).
- area with residential built-up areas, valley floor (Bema St., No. 5).
- area with blocks of flats, 50 m above the valley floor, south of city centre (Bojki St., No. 6).
- area with residential built-up areas, 50 m above the valley floor, south of city centre (Czajna St., No. 7).
- area with residential built-up areas, 50 m above the valley floor, north of city centre (Ojcowska St., No. 8).
- rural area in the valley floor (Jeziorzany, No. 9), 50 m above the valley floor, south (Rzozów, No. 10) and north (Modlniczka, No. 11) of city centre, and at the hill top 100 m above the valley floor, south of city centre (Libertów, No. 12).

The properties of the surroundings of the measurement points are described in detail in Bokwa *et al.* (2015). Each point has been equipped with an air temperature data logger (HOBO® PRO series Temp Data Logger, Onset Computer Corporation, Pocasset, MA, USA; operating range T, –30 to 50°C; resolution, 0.2°C between 0 and 40°C). All of them were supplied with naturally ventilated solar radiation shields. The loggers were located 2–4 m above the ground, depending on the local conditions and safety demands.

The data with 5-minute temporal resolution were used from 5 rural points and 6 urban points described above so as to calculate the night-time course of UHI magnitude (18–09 UTC) in various types of land use and two vertical zones: valley floor and 50 m above it, south or north of the valley floor, following the method described in Bokwa *et al.* (2015). Air temperature inversion in the river valley was calculated as the difference in air temperature (5-min. resolution, 18–09 UTC) between Jeziorzany and Libertów.

To distinguish the differences in the influence of fog on UHI magnitude in 2010–2015, mean night-time courses of UHI magnitude were presented for the groups of nights mentioned, using the same statistic tests as for the period 2006–2015. Table 1 shows the combination of conditions considered in the comparisons (shaded fields). For each combination (field), nine pairs of data series were compared, i.e., eight night-time UHI magnitude's courses and the course of temperature difference between Jeziorzany and Libertów, for two fog/weather type combinations.

As atmospheric circulation is one of the most important factors controlling weather conditions, the results were additionally analyzed with the calendar of circulation types for the territory of Southern Poland by T. Niedźwiedź (1981, available at: http://klimat.wnoz.us.edu.pl/#!/glowna, extended by the Author, 2016). A short description of the calendar structure is provided in Bokwa *et al.* (2018), and all the classification schemes can be found in the cited literature (Niedźwiedź, 1981, 2000, 2016).

Cluster analysis (k-means method) was used in order to distinguish types of spatial and temporal UHI structure during nights with fog. Each night with fog was an element to be grouped and it was defined with a sequence of the nine data series mentioned above, organized in the same order for all nights. Therefore, each sequence represented the temporal and spatial pattern of UHI in the western part of Kraków during a certain night. Moreover, for each night

Table 1. Combinations of fog occurrence options and night-time weather types for which pairs of data series were tested with the Wald-Wolfowitz test, Kolmogorov-Smirnov tests and U Mann-Whitney test (shaded fields).

Weather type	Fog occurrence	no fog	RWT		
			B and BG	B only	BG only
RWT	B and BG	[shaded]			
	B only	[shaded]			
	BG only	[shaded]			
NRWT	B and BG	[shaded]	[shaded]		
	B only	[shaded]		[shaded]	
	BG only	[shaded]			[shaded]

the following parameters were added: fog occurrence option, fog intensity, weather type, atmospheric circulation type, UHI magnitude calculated as $T_{min}BG–T_{min}B$, values of maximum UHI magnitude in each of the eight UHI courses, index of UHI variability (i.e., difference between maximum and minimum value from the eight maximum UHI magnitudes mentioned), and the value of maximum vertical air temperature difference during a night. The parameters described were used to interpret the outcome of cluster analysis. Mean UHI and air temperature inversion courses were also calculated for RWT nights without fog as in such conditions UHI magnitudes are the highest.

RESULTS AND DISCUSSION

Fog and UHI Magnitude, 2006–2015

In the cold half-year of 2006–2015, there were 208 nights with RWT and in 27% of them fog was noted at 06 UTC, either at one or at both stations. From the remaining 1614 nights with NRWT, only in 9% did fog occur at 06 UTC (Table 2), as fog formation is most effective during non-advective conditions, especially with a clear sky, which favors radiative cooling and water vapor condensation. In Balice, the frequency of thin fogs was 32.5%, moderate fogs: 45.0% and dense fogs: 22.5%. In Botanical Garden the values were: 42.2%, 34.0% and 23.8%, respectively.

Table 2 shows basic descriptive statistics of UHI magnitude, while Fig. 2 presents frequencies of UHI magnitudes. Although the highest mean UHI magnitude (2.3 K) is observed during the nights without fog (RWT, Table 2), the highest value of the most frequent UHI magnitude is not connected with nights without fog but with nights when fog was noted at Balice only (1.6–2.0 K and 2.1–2.5 K, respectively, Fig. 2). When fog occurred at Botanical Garden only, the most frequent values (> 35% of cases) decreased to the range 0.5 to 1.0 K. Fog is noted most often at both stations (Table 2); however, UHI magnitude in such situations is most frequently from 1.1 to 1.5 K (Fig. 2(A)). The values exceeding 3.6K are noted only on days without fog, therefore, in conclusion, it can be stated that fog presence is connected with a decrease in UHI magnitude, which is in accordance with the findings by, for example, Li *et al.* (2012), Gough and He (2015), Tam *et al.* (2015).

In the cold half-year of 2006–2015, there were 139 nights with fog at 06 UTC at one or both stations which occurred during NRWT. It was usually the cloudiness which exceeded 2/8, whereas the wind speed in most of the cases stayed low (Table 3). When the fog was noted at Balice only, wind speed never exceeded the value of 2 m s^{-1}, but the cloudiness was always above 2/8 at least at one of the stations; most often (about 50%) it was above 7. In the case of fog either at Botanical Garden only or at both stations, a clear difference in wind speed can be seen between the stations; at Botanical Garden almost in all cases the wind speed was up to 2 m s^{-1}, while at Balice, in about 35% of cases it reached 3–5 m s^{-1}. This shows the impact of urban structures on the increase in roughness and the decrease in wind speed. Cloudiness most often exceeds 7/8 at both stations. The data show that fog can occur in Kraków at various combinations of wind speed and cloudiness. In the case of fog noted at one station only (Table 2), mean UHI magnitudes are almost the same, regardless of accompanying wind and cloudiness conditions, while for fog at both stations or nights without fog, UHI magnitudes are much lower during the nights with wind speed above 2 m s^{-1} and cloudiness above 2/8. This suggests that in the case of Kraków, fog occurrence at one of the stations is a more important factor controlling UHI magnitude than cloudiness and/or wind speed. Such fog options are linked to local climate effects, connected with the impact of relief mentioned above, as when fog is observed at both stations it is usually due to

Table 2. Mean, minimum and maximum UHI magnitudes (K) together with standard deviation values, for particular fog occurrence options at 06 UTC and nights with RWT and NRWT, in the cold half-year of 2006–2015 in Kraków.

Fog option	RWT				NRWT			
	B and BG	B only	BG only	No fog	B and BG	B only	BG only	No fog
Mean	1.5	2.1	1.4	2.3	1.0	2.0	1.2	1.4
Min	–0.1	0.6	0.2	–0.2	–0.4	0.5	0.0	–1.6
Max	3.0	3.4	2.9	5.3	3.4	4.6	3.3	6.0
Stand. dev.	0.8	0.7	0.9	1.1	0.9	0.8	1.0	1.0
No. of cases	31	18	8	151	71	31	37	1475

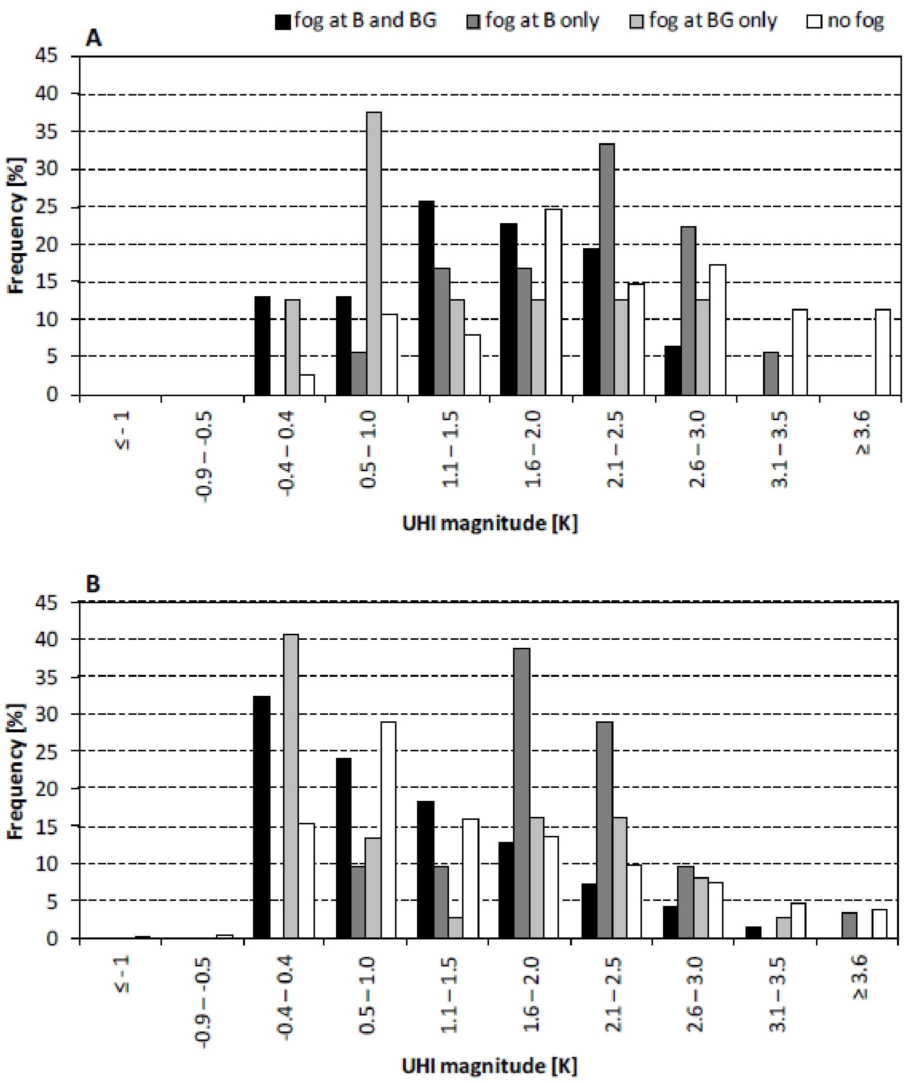

Fig. 2. Frequency (%) of UHI magnitude values during the nights with and without fog at 06 UTC, at RWT (A) and NRWT (B), in the cold half-year of 2006–2015 in Kraków.

Table 3. Frequency (%) of particular values of wind speed and cloudiness in nights with and without fog at 06 UTC, NRWT, in Kraków, 2006–2015.

Fog option		B and BG		B only		BG only		No fog	
v and N		B	BG	B	BG	B	BG	B	BG
v (m s^{-1}):	0–2	66.2	98.6	100.0	100.0	62.2	94.6	45.4	78.4
	3–5	33.8	1.4	0.0	0.0	35.1	5.4	38.2	20.6
	6–8	0.0	0.0	0.0	0.0	2.7	0.0	13.2	0.9
	9–10	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0
	> 10	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
N:	0–2	0.0	0.0	16.1	6.5	10.8	8.1	7.5	9.8
	3–4	2.8	0.0	12.9	16.1	16.2	10.8	7.7	8.2
	5–6	2.8	1.4	22.6	22.6	8.1	0.0	11.9	10.3
	≥ 7	94.4	98.6	48.4	54.8	64.9	81.1	72.9	71.7
	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

large-scale synoptic processes. Fig. 2(B) shows that for all options of fog occurrence there is a shift in the frequency values in comparison to Fig. 2(A), i.e., the most frequent UHI magnitudes are smaller during increased wind and/or cloudiness than during clear nights. The sequences of the frequencies of UHI magnitude values, shown in Figs. 2(A) and 2(B), were analyzed with nonparametric tests: Wald-Wolfowitz test, Kolmogorov-Smirnov test and U Mann-Whitney test, in order to see whether there are statistically significant differences between series representing the following:

a. various fog options and no fog conditions during clear nights;
b. various fog options and no fog conditions during cloudy and/or windy nights;
c. particular fog options during clear nights and cloudy and/or windy nights.

For all options it was found that the differences are not statistically significant, either at $p < 0.01$ or $p < 0.05$. One of the reasons of such results might be that the station located in Botanical Garden has certain limitations as a point representative for the local climate of the city center's urban built-up, due to the mitigating effect of the vegetation. Additionally, no statistically significant relationship was found between fog intensity and UHI magnitude.

Data for the period 2006–2015 present relationships between UHI magnitude and fog only for the valley floor (in terms of land form) and only for urban green areas (in terms of land use). The next section shows a much more complete image for the period 2010–2015.

Fog and UHI Magnitude, 2010–2015

In the cold half-year of 2010–2015, there were 119 nights with fog at 06 UTC at one or both of the stations and 29 of them occurred at RWT (Table 4).

For each combination of fog occurrence and weather option, mean courses of UHI magnitude were calculated (18–09 UTC, 5-min. resolution), as air temperature differences between the following points (numbers as in Fig. 1): A. valley floor: No. 1–No. 9, No. 2–No. 9, No. 3–No. 9, No. 4–No. 9, No. 5–No. 9; B. 50 m above the valley floor, south: No. 6–No. 10, No. 7–No. 10; C. 50 m above the valley floor, north: No. 8–No. 11. The difference between points 9 and 12 was calculated in the same way in order to indicate the air temperature inversion. The impact of fog on UHI was studied by comparison of the mean series obtained and checking whether there are statistically significant differences between them. Most often all the tests used showed that the differences are significant ($p < 0.5$) but some spatial variability can be seen. Tables 5–7 present the cases for which particular tests show no statistically significant differences (shadings following the pattern presented in Table 1).

All tests used indicate that in the case of UHI in residential built-up areas located 50 m above the valley floor (south, No. 7–No. 10), there is no significant fog impact in cases where the phenomenon is noted in Balice only (RWT). For other series analyzed, the outcomes are less clear. Both Wald-Wolfowitz and U Mann-Whitney tests show that in the case of UHI in residential built-up areas located 50 m above the valley floor (north, No. 8–No. 11),

Table 4. Number of nights with particular weather type in the cold half-year 2010–2015 in Kraków.

Fog option	B only	BG only	B and BG	No fog
RWT	10	7	12	56
NRWT	18	22	50	918

Table 5. Data series and fog/weather type combinations for which no statistically significant difference was found according to the Wald-Wolfowitz test ($p < 0.5$).

Night type	Fog option	no fog	RWT		
			B and BG	B only	BG only
RWT	B and BG				
	B only	No. 1–No. 9 No. 7–No. 10			
	BG only	No. 7–No. 10 No. 8–No. 11			
NRWT	B and BG				
	B only			No. 8–No. 11	
	BG only				

Table 6. Data series and fog/weather type combinations for which no statistically significant difference was found according to the Kolmogorov-Smirnov test ($p < 0.5$).

Night type	Fog option	no fog	RWT		
			B and BG	B only	BG only
RWT	B and BG				
	B only	No. 7–No. 10			
	BG only				
NRWT	B and BG				
	B only				
	BG only				

Table 7. Data series and fog/weather type combinations for which no statistically significant difference was found according to the U Mann-Whitney test ($p < 0.5$).

Night type	Fog option	no fog	RWT		
			B and BG	B only	BG only
RWT	B and BG	No. 7–No. 10			
	B only	No. 1–No. 9			
		No. 5–No. 9			
		No. 7–No. 10			
	BG only	No. 8–No. 11			
NRWT	B and BG	No. 3–No. 9	No. 6–No. 10		
		No. 8–No. 11	No. 8–No. 11		
		No. 9–No. 12			
	B only	No. 1–No. 9		No. 6–No. 10	
		No. 2–No. 9		No. 8–No. 11	
		No. 3–No. 9			
		No. 4–No. 9			
	BG only				

the UHI night-time courses are not affected by fog presence in the city center (RWT) and in cases where fog is noted in Balice only, the courses show no dependence on weather conditions. The two tests also show that UHI in green areas in the city center (No. 1–No. 9) shows no impact of fog if the phenomenon is noted in Balice only (RWT). The outcomes of the U Mann-Whitney test suggest mainly that at NRWT the presence of fog shows no impact on the course of UHI, regardless of the land form and the land use.

The above analyses were designed with initial assumptions concerning the division of the data available into groups of nights with defined weather conditions. In order to further study the impact of fog on UHI, cluster analysis (k-means method) was used, i.e., the data were grouped so as to gather in each cluster the most similar elements and make the differences among the clusters the largest. Due to a slight lack of data on particular days with fog, cluster analysis was completed using data series from 107 days. Fig. 3 shows mean values of the elements for the three clusters distinguished and Table 8 presents the accompanying information for each cluster. The clusters were obtained using data on nights with fog at 6 UTC. Therefore, Fig. 3(D) shows mean courses of UHI and air temperature inversion for the nights with RWT and no fog as the highest UHI magnitudes are usually linked to such conditions. Cluster 2 shows the largest values of UHI and air temperature inversion, comparable to those shown in Fig. 3(D), while cluster 3 shows the smallest values and the smallest spatial variability of UHI in Kraków. Cluster 1 presents a transitional situation. Analysis of Table 8 allows us to state that the spatial and temporal UHI structure presented by cluster 2 occurs most rarely. Mean maximum UHI values are the highest and vary from 2.1 to 5.9 K; they decrease with height above the valley floor. The inversion is the strongest in comparison to other clusters and its mean maximum value reaches 7 K. Such a UHI/inversion pattern is linked exclusively to anticyclonic weather situations and most often to RWT. In most cases, fog occurs in Balice only, and all fog intensity classes have almost the same frequency. However, the fog in Balice is not too thick as either clear sky or clouds are observed at that station at 06 UTC. In such conditions, in rural areas west of Kraków, in the valley floor, cold-air reservoirs are created due to katabatic flows, so fog occurrence is one of the consequences of those processes. It can be assumed that in such situations fog modifies UHI only in the areas located in the valley floor as it does not have a large vertical extent. In order to check that hypothesis, series shown in cluster 2 and Fig. 3(D) were tested with the same statistical tests as other series analyzed above. Only in the case of the series concerning No. 7–No. 10 did all tests show no significant difference between the two series, which might be considered as a result supporting the hypothesis. Another argument can be found in Fig. 3(B) showing data for cluster 2. The UHI courses for the valley floor show a decrease after midnight, while in the case of UHI courses for the points located 50 m above the valley there are increasing tendencies. This most probably shows the effect of a gradual increase in fog extent and intensity. However, UHI magnitude remains very diversified as the fog occurs only in Balice (i.e., only in the rural area), so in urban areas classical UHI-forming processes prevail. In the case of cluster 1, the decrease in both UHI magnitude and spatial variability can be seen after midnight and it concerns almost the whole city, except UHI values No.7–No. 10, already mentioned above. In this cluster fog occurrence at both stations is most frequent, which explains such a clear impact of fog formation on the decrease in UHI magnitude all over the city. Additionally, during over 30% of nights included in that cluster, wind speed exceeded $2\ m\ s^{-1}$, which is a factor increasing turbulence and air mixing and decreasing air temperature differences. According to Morawska (1966), fog in Kraków usually forms at 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. In the case of cluster 3, the largest one (i.e., representing the conditions which occur most often), UHI values all over the city and all night long are rather uniform and do not exceed 2 K. Data on cloudiness suggest that such situations are linked to cloudy weather, with Stratus clouds, the fog vertical extent

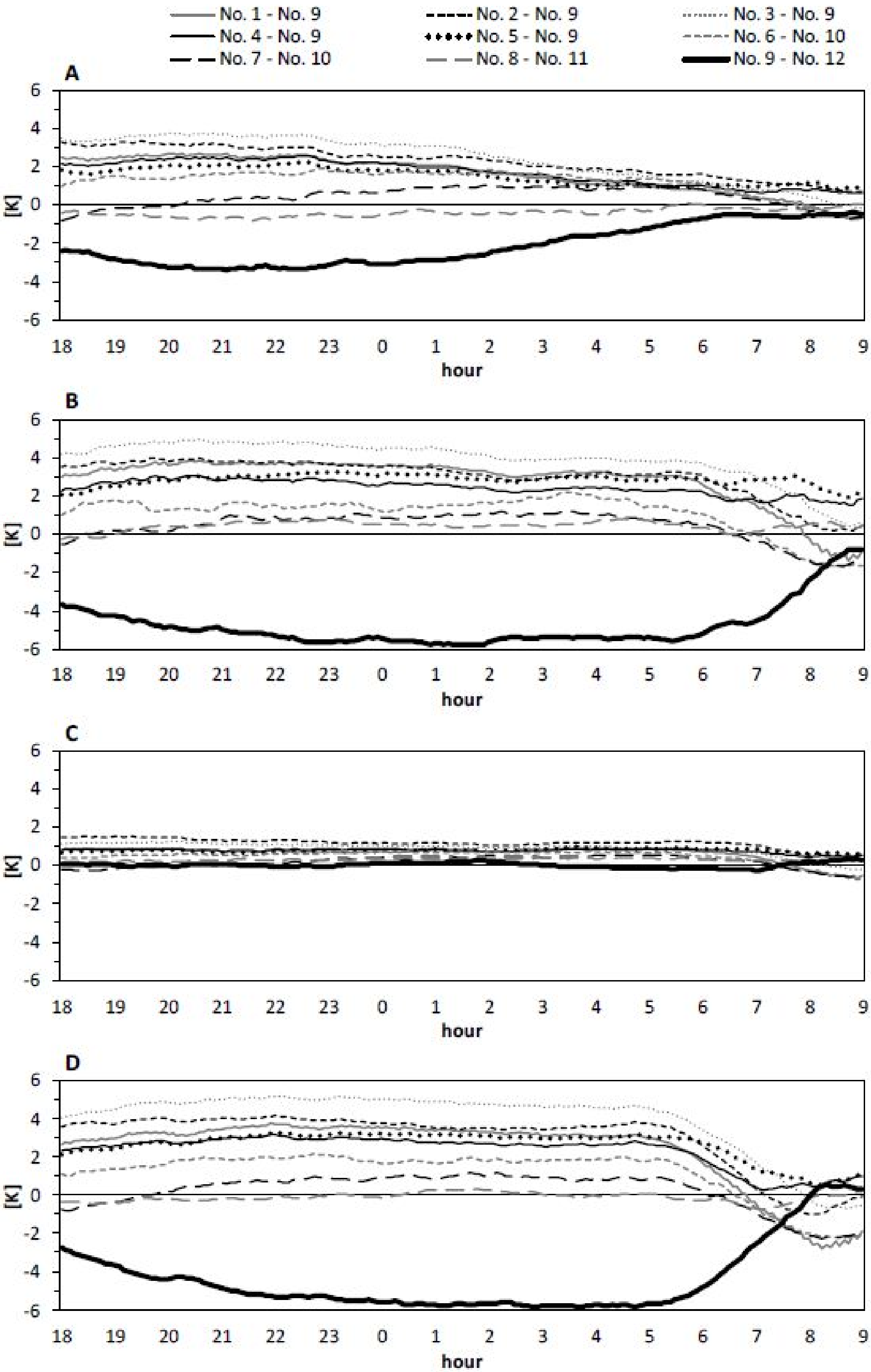

Fig. 3. Mean courses of UHI and air temperature inversion in particular clusters distinguished (A: cluster 1, B: cluster 2, C: cluster 3) and during the nights with RWT and no fog in Kraków (D), 2010–2015.

is very large and fog is often formed before the evening begins, so it affects night-time UHI formation from the beginning. There is no temperature inversion as isothermal conditions can be observed all night long. Fog occurs most often at both stations and probably due to regional scale processes, not local impacts. In this cluster dense fog occurs least often, in comparison to other intensity classes, at both stations. Additionally, during about 50% of nights included in that cluster, wind speed exceeded 2 m s^{-1}, which is an additional cause of small air temperature differences. No statistically significant relationship was found between fog intensity and UHI magnitude.

Table 8. Parameters characterizing the clusters distinguished.

Parameter	units	Index	Cluster 1	Cluster 2	Cluster 3
		number of elements	31	20	56
Mean maximum UHI magnitude	K	No. 1–No. 9	3.6	4.7	1.8
		No. 2–No. 9	4.2	5.0	2.4
		No. 3–No. 9	4.7	5.9	2.2
		No. 4–No. 9	3.4	4.1	1.8
		No. 5–No. 9	3.2	4.5	1.9
		No. 6–No. 10	3.1	3.7	1.6
		No. 7–No. 10	2.0	2.6	1.2
		No. 8–No. 11	1.2	2.1	1.1
Additional UHI characteristics		Mean spatial UHI variability	3.8	4.1	1.8
		Mean UHI ($T_{min}BG – T_{min}B$)	1.3	2.2	0.9
Air temperature inversion		Mean maximum inversion	–3.8	–7.0	–0.9
Fog occurrence option	% of days in a cluster	B and BG	64.5	15.0	58.9
		B only	12.9	80.0	8.9
		BG only	22.6	5.0	32.1
Fog intensity option		Int. = 0 at B	16.1	35.0	21.4
		Int. = 1 at B	35.5	30.0	26.8
		Int. = 2 at B	25.8	30.0	19.6
		Int. = 0 at BG	29.0	5.0	48.2
		Int. = 1 at BG	22.6	10.0	30.4
		Int. = 2 at BG	35.5	5.0	12.5
Weather type		RWT	19.4	55.0	14.3
atmospheric circulation type		anticyclonic circulation types	71.0	100.0	69.6

CONCLUSIONS

Fog microstructure, e.g., droplets size and their concentration number, has a significant impact on liquid water content (LWC), which can contribute to air cooling as fast as up to 5°C per hour when LWC = 0.3 g m^{-3} (Welch and Wielicki 1986; Gultepe *et al.*, 2007). Nevertheless, in urban environments the relationship is not straightforward due to the number of fog favoring and limiting factors (Gultepe *et al.*, 2007, 2009). High number concentration of aerosols increases fog vertical extent and leads to high liquid water content. However, due to the different physical properties of urban aerosols the processes shaping fog microstructure over cities are more intricate influencing also other parameters as visibility or air temperature (Gultepe *et al.*, 2007).

Therefore, the links between UHI intensity and fog density are rarely discussed, especially in quantitative context. For example, in Los Angeles (USA), climate records showed that dense fog has reduced by a factor of two at two busy, coastal airports during the period 1950 to 2004, due to increase in the UHI, decreasing aerosols concentrations and moisture deficit (LaDochy, 2005). On the other hand aerosols may inhibit fog formation because they provide a source of condensation nuclei in the city which results in greater competition for vapor and a larger number of smaller droplets which do not produce the very dense type of fog (Oke, 1987). Relatively large values of UHI intensity were observed sometimes during conditions of fog measured at the suburbs of Utrecht. For these conditions, the large temperature differences between the city and rural area could also partly be caused by spatial fog differences caused by the city (Brandsma, Wolters, 2012).

The situation is even more difficult in regions of complex and heterogeneous terrain where mainly during radiative weather conditions cold-air drainage flows from the mountains or hills into the valleys which is one of fog-favoring factors (Gultepe *et al.*, 2006; Müller *et al.*, 2007). The study realized in Zurich airport area showed that the spatial distribution of air temperature, humidity and fog characteristics is very diversified, especially in vertical profile, with the most dense fog occurrence in the valley bottom (Gultepe *et al.*, 2006).

The results obtained in the present study, conducted for urban area of Kraków located in a river valley, for both periods (2006–2015 and 2010–2015) and both data sets show that UHI values and their spatial pattern during the nights with fog at 6 UTC are highly diversified. First of all, the impacts of weather conditions on UHI magnitude and spatial pattern are decisive. In the case where fog occurs during particular weather conditions, some factors which are important for UHI formation are modified. During the nights with RWT (as shown with cluster 2), cold air reservoirs formed in rural areas enhance fog occurrence but, on the other hand, fog formation raises minimum air temperature and decreases UHI magnitude in the valley floor. In the case of cities located in concave land forms, like Kraków, the impact of fog on UHI spatial pattern depends also on the vertical extent of fog. Areas in the valley floor are always the subject of fog influence, but the city areas located 50 m above the valley floor are often above the fog layer and UHI magnitude there is not affected by fog. It can be concluded that fog impact on UHI is the strongest during RWT and anticyclonic synoptic situations, and usually limited to the valley floor, while during other weather conditions, cloudiness and wind speed are the main factors controlling UHI and the role of fog is much smaller or negligible. In terms of the quantitative impact of fog on UHI, the data for cluster 2 show a decrease in UHI magnitude by about 1 K between the first and the second phases of stabilization. The comparison of results for cluster 2 and RWT and no fog (Figs. 3(B) and 3(D)) shows that UHI values during the first part of the night are almost the same in both cases. Therefore, the drop in UHI magnitude observed in the valley floor can be attributed to fog formation. As fog impact is most pronounced for that cluster, the value of 1K may be considered representative for the extent of that impact. The results presented show the important role of particular local environmental conditions in fog formation and resulting diversified fog occurrence, either at one of the stations or at both of them. Nevertheless, regarding data limitation, detailed quantitative analysis of the relationship between fog occurrence and UHI cannot be conducted. To precise the correlation ratio and to define the role of particular factors, e.g., fog intensity further investigation including fog microstructure measurements complemented with the analysis of satellite data in order to study the spatial patterns of fog occurrence in a local scale in more detail is necessary. Such studies would allow researchers to obtain data on the spatial distribution of fog to be used not only for UHI studies, but also air pollution issues.

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