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ORIGINAL PAPER

The influence of atmospheric circulation on the intensity of urban heat island and urban cold island in Poznań, Poland

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Abstract The study has analyzed influence of an atmospheric circulation on urban heat island (UHI) and urban cold island (UCI) in Poznań. Analysis was conducted on the basis of temperature data from two measurement points situated in the city center and in the Ławica airport (reference station) and the data concerning the air circulation (Niedźwiedź's calendar of circulation types and reanalysis of National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR)). The cases with UHI constitute about 85 % of all data, and UCI phenomena appear with a frequency of 14 % a year. The intensity of UHI phenomenon is higher in the anticyclonic circulation types. During the year in anticyclonic circulation, intensity of UHI is 1.2 °C on average while in cyclonic is only 0.8 °C. The occurring of UHI phenomena is possible throughout all seasons of the year in all hours of the day usually in anticyclonic circulation types. The cases with highest UHI intensity are related mostly to night-time. The cases of UCI phenomena occurred almost ever on the daytime and the most frequently in colder part of the year together with cyclonic circulation. Study based on reanalysis data indicates that days with large intensity of UHI (above 4, 5, and 6 °C) are related to anticyclonic circulation. Anticyclonic circulation is also promoting the formation of the strongest UCI. Results based on both reanalysis and the atmospheric circulation data (Niedźwiedź's circulation type) confirm that cases with the strongest UHI and UCI during the same day occur in strong high-pressure system with the center situated above Poland or central Europe.

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1 Introduction

The process of urbanization has a significant impact on the properties of the surface of the earth and the atmosphere. The characteristic features of the urbanized areas cause the positive air temperature anomalies in comparison with surrounding areas what is called as the urban heat island (UHI) phenomenon (Oke 1978).

The intensity of UHI is calculated as a difference between urban and rural air temperatures and depends on many factors such as the following: the size of the city and its population, topography, climate zone, and meteorological conditions (Oke et al. 1991). Considering the synoptic conditions, the biggest influence on the UHI intensity is cloudiness and wind speed. The intensity of UHI reaches the highest values under cloudless sky and light wind conditions (Montavez et al. 2000; Morris et al. 2001).

As can be seen from the previous papers considering this research problem, the maximal intensity of UHI occurs during anticyclonic synoptic situations (Yague et al. 1991; Unger 1996). Additionally, Morris and Simmonds (2000) show that the intensity of UHI depends on the position of the center of the high pressure and the dominant direction of the air advection, but they also indicate that the lowest UHI intensity does not occur under cyclonic synoptic situations but under northwestern advection coming from anticyclonic circulation. An interesting approach to the problem was shown by Mihalakakou et al. (2002) using the neural network model to the simulation of UHI under different synoptic types.

As the most of recent UHI research has focused on typically optimal for UHI initial conditions (clear sky and windless or near windless weather events), significantly less details are known about the relationship of UHI intensity and various synoptic conditions. In the previous research undertaking the UHI and synoptic condition, many authors calculated UHI

and intensity based on before-divided categories of synoptic conditions (Unwin 1980; Yague et al. 1991) or taking into consideration the groups of UHI cases (depending of their magnitude), and composite techniques revealed influence of the prevailing synoptic conditions on various UHI magnitudes (Morris and Simmonds 2000).

Research results concerning average intensity of UHI show a clear relationship between city size and the intensity of UHI. The maximal intensity of the UHI is a linear function of the logarithm of the population. In large American cities during favorable weather conditions, the intensity of UHI can exceed 12 °C while in European cities often reach 10 °C (Oke 1973). The highest maximum UHI in Rotterdam is in late spring and summer with 95 percentile values from 4.3 °C to more than 8 °C (Steeneveld et al. 2011; van Hove et al. 2014). In Madrid, the maximal intensity of UHI in the summer months can reach 5 °C (Fabrizi et al. 2011), while in Rome, 3–4 °C during nighttime and negative or almost zero UHI intensity during daytime (Fabrizi et al. 2010).

Previous studies concerning the UHI phenomena in Poznań were conducted only on 1-year data period from years 1992–1993 (Koczorowska 1995). Last study based on the period 2008–2011 conducted in the Department of Climatology Adam Mickiewicz University in Poznań indicates that the UHI phenomenon is commonly occurring in the central areas of the city. The mean annual intensity of UHI is about 1 °C. However, the maximal UHI exceeds 7 °C. It is also known that maximal intensity of UHI and urban cold island (UCI) phenomena in Poznań is more noticeable in the warm half of the year (doctor dissertation by Busiakiewicz 2011).

The main objective of this paper is to characterize the UHI and UCI phenomena under various synoptic conditions in the city of Poznań, based on the in situ measurement data from two measurement points located in the city center and the airport area in the period 2008–2013.

1.1 Study area

Poznań as the capital of Greater Poland Voivodeship belongs to the biggest cities in Poland. The area is equal to 261.85 km^2, and population exceeds 500,000 inhabitants. Poznań with the range of altitudes from 60 to 151 m above sea level is situated in the Warta river valley. In the boundaries of Poznań are located several natural (glacial origin) and artificial lakes. The general surface of water bodies is 1.9 % of whole area of the city. The most of the Poznań's territory lies on the plateau areas (58 %), 7 % in the Warta river valley, and 35 % in the glacial channels and on the upper river terraces (Bartkowski and Krygowski 1959; Kowalik 2005).

Mean annual air temperature in Poznań is 8.3 °C with the hottest month July (18.1 °C) and the coldest January (−1.6 °C). The Wielkopolska Region is characterized by the lowest total rainfall in Poland. The average annual precipitation reaches 517 mm (max July—75 mm; min February—26 mm). Due to location of the study area, this region with the frequency of about 70 % is reached by the polar air masses from the western direction; significantly less frequent are polar continental and arctic with tropical air masses (Woś 2010).

Analyzing the historical and current development of the city, it may be stated out continuous spread of suburban areas and, thus, change in character of land cover types surrounding central parts of Poznań. Over the years, there has been observed an increase in surface area of 76.9 km^2 in the year 1939 to the present 261.85 km^2 with the increase of the number of residents from 273.6 thousand to 554.2 thousand, respectively. Currently, the population density is 2117 persons/km^2. The historical center is surrounded by scattered forms of development which includes large areas of modernist housing estates and single-family housing. The green areas include forests, agricultural land in the peripheral zones, and the wedge-ring system of green urban areas. This system consists of four green wedges that radiate out from the center to the borders and three concentric rings inside the city. Built-up areas occupy 43 % of the urban administrative area of Poznań. The housing areas constitute 28.6 %, road and transport networks with associated lands 30.6 %, and industrial areas 10.9 % (Fig. 1) (Central Statistical 2012).

2 Data and methods

To calculate the UHI and UCI intensity, two measurement points were selected: Piekary (52° 24′ 19.96″ N, 16° 55′ 39.60″ E; altitude 73 m above sea level (a.s.l.)) as the point located in the city center with the highest values of air temperature and the reference (rural) station of Ławica airport (52° 24′ 59.46″ N, 16° 50′ 4.71″ E′; altitude, 86 m a.s.l.). Piekary measurement point is located in the city center in continuous urban fabric. Ławica point is located at the airport in the western part of Poznań, ca. 7 km from the city center. Due to the peripheral location of this station (flat, open area) and the land cover, Ławica point is treated in this paper as the reference station (Fig. 1). Similar methodology (using the airport station as the reference station) was used in other studies, e.g., in polish cities as Wrocław, Kraków, and Warszawa (Stopa-Boryczka et al. 2001; Szymanowski 2004; Bokwa 2010). According to Koczorowska and Farat (2006), the rural nature of Ławica station is confirmed by the studies showing that the average annual air temperature differences between Ławica and meteorological stations sited around Poznań do not exceed 0.1 °C and up to 80 % of daily mean values vary about 0.0–0.2 °C.

Meteorological data from the point Piekary were taken from the automatic data logger HOBO U23-001 (accuracy: 0.2 °C). The HOBO logger was placed in an antiradiation
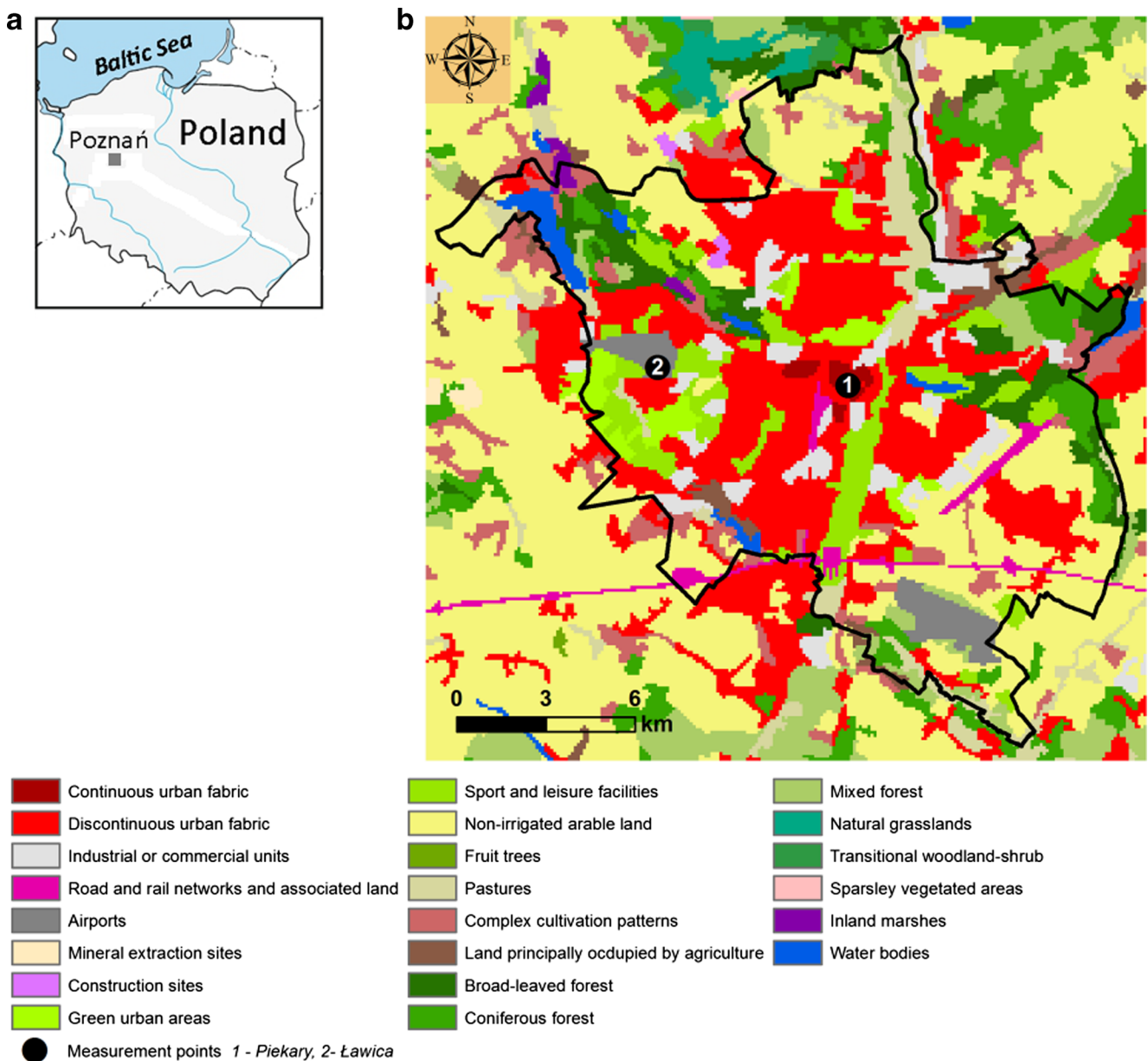
Fig. 1 Location of the city of Poznań in Poland (**a**) and measurement points and types of land cover in Poznań according to Corine Land Cover 2006 (**b**)

shield at standard height (2 m above ground level). Data from the reference station (Ławica) were taken from the Institute of Meteorology and Water Management (sensor: VAISALA HMP45d on the standard screen; accuracy, 0.2 °C). Temporal resolution of both data sets is equal to 30 min (94, 950 cases with 3.6 % lack of data). The data refer to the period of April 2008 to September 2013. The intensity of UHI and UCI was defined as the air temperature difference (ΔT) between city center (T_C) and rural areas (T_R). The air temperature difference (ΔT) above or below 0 °C means the occurrence of UHI or UCI phenomenon, respectively.

To calculate seasonal basic statistics of UHI and UCI, it was assumed, according to meteorological definition of seasons, that the year is divided into four periods of 3 months

each: winter defined as December–February, spring as March–May, summer as June–August, and autumn as September–November (AMS 2001).

In order to investigate relation of UHI or UCI phenomenon and atmospheric circulation, daily data of the Niedźwiedź's calendar of circulation types for Western Poland (http://klimat.wnoz.us.edu.pl/) and National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis with spatial resolution of the grid data 2.5×2.5-degree (Kalnay et al. 1996) were used.

Using the data concerning different types of air circulation, the frequency and magnitude of UHI and UCI in the particular types were calculated. The Niedźwiedź's calendar of

circulation types consists of 21 circulation types of which 10 (1–10) is treated as anticyclonic and 10 (11–21) as cyclonic (Table 1) (Niedźwiedź 2013).

To estimate influence of synoptic situations on the occurrence of extreme values of UHI and UCI in Poznań, NCEP/NCAR Reanalysis data were used. As extreme cases were selected, values equal to 99 and 1 percentile of half-hourly data. The 99 percentile for used data set is 4.37 °C, and the 1 percentile is equal to −0.97 °C. Finally, as a criterion to choose extreme cases, we selected data above 4 °C and below −1 °C. The data were grouped into seven groups:

1. The air temperature in the city center (T_c) is 3 °C lower than in the reference station (T_R)-(UCI $\leq$−3 °C) (5 days).
2. −3 °C<UCI$\leq$−2 °C (15 days).
3. −2 °C<UCI$\leq$−1 °C (202 days).
4. 4°C<UHI$\leq$5 °C (56 days).
5. 5°C<UHI$\leq$6 °C (106 days).
6. UHI >6 °C (19 days).
7. The seventh group encompasses days when the intense UHI (>4 °C) and intense UCI ($\leq$−1 °C) appeared on the same day (90 days).

Table 1 Circulation types for Western Poland

Code	Type	Code type description
1.	Na	North (direction of air masses advection, geostrophic wind)
2.	NEa	Northeast
3.	Ea	East
4.	SEa	Southeast
5.	Sa	South
6.	SWa	Southwest
7.	Wa	West
8.	NW	Northwest
9.	Ca	Central anticyclone situation (high center)
10.	Ka	Anticyclonic wedge or ride of high pressure
11.	Nc	North
12.	NEc	Northeast
13.	Ec	East
14.	SEc	Southeast
15.	Sc	South
16.	SWc	Southwest
17.	Wc	West
18.	NWc	Northwest
19.	Cc	Central cyclonic, center of low
20.	Bc	Through of low pressure (different directions of air flow and frontal system in the axis of through)
21.	x	Unclassified situations or pressure col.

Anticyclonic types, 1–10; cyclonic types, 11–20

For each group, the composite maps showing sea-level pressure (SLP) distribution and 500-hPa geopotential height for chosen area of Europe were constructed. To show the mean synoptic conditions for the average year, mean SLP and mean geopotential height 500 hPa maps were computed.

3 Results

### 3.1 Annual, seasonal, and diurnal course of the intensity of UHI and UCI

Higher air temperature in the center of Poznań occurs in more than 85 % of all cases of the investigated period (Fig. 2). The cases with surpluses air temperature in the city center between 0 and 0.5 °C constitute 28 % of all cases. Intensity of UHI in more than half of the all data set does not exceed 1 °C and in 70 % is not higher than 2 °C. In the range of 2–3 °C, investigated phenomenon is observed in about 7 % cases. Intensity over 3 °C constitutes only about 4 % and above 4 °C slightly more than 1 % of all UHI cases. In turn, UCI appears with a frequency of about 14 % a year and the vast majority of them not exceeding −0.5 °C (Fig. 2).

The UHI in Poznań is a dynamic phenomenon with high daily and seasonal variability. As shown in Fig. 3, the average and maximum values of UHI can occur almost throughout the year with the highest frequency in the period from March to November. In mentioned period during nights, UHI represents over 86 % of all cases. For comparison, in winter's nights, UHI frequency is 78 %.

The cases with the greatest UHI appear in the first decade of May, in mid-June, and at the turn of September and October especially during night hours. Lower UHI values occur in the time frame between March and October during day's hours. The lowest intensity of UHI or UCI phenomenon is most frequent especially during winter months and can appear all over the year during the morning and evening transition periods. The average intensity of UCI throughout the year in the vast majority is in the range of 0.0–0.5 °C, and only in September and October, there are few cases in the range of 0.5–1.0 °C. Explicitly privileged hours to occurrence of UCI are 7–10 UTC and 12–15 UTC in the period from third decade of September to the end of November and the first half of March. In turn, in winter, a few cases of UCI occurred in different hours of the day (Fig. 3).

Annual and seasonal UHI and UCI daily mean intensity and mean daytime and nighttime values separately were calculated. The daytime and the nighttime periods were taken on the basis of everyday sunrise and sunset hours for Poznań coordinates (φ 52° 24′ 30″, λ 16° 56′ 03″). The average annual UHI intensity in the investigated period is 1.0 °C. Annual day and night UHI intensities reach 0.86 and 1.19 °C, respectively. The highest average of UHI has nights during summer

Fig. 2 Histogram of urban-rural temperature differences observed in Poznań in the period April 2008–August 2013
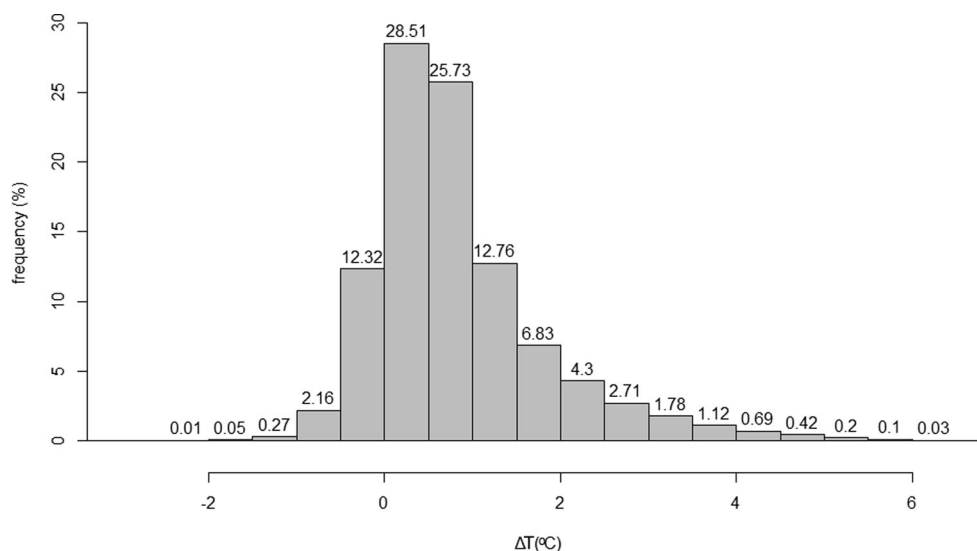
(VI–VIII) and spring (III–V) with values of 1.6 and 1.5 °C, respectively. During the winter (XII–II), UHI value is only 0.7 °C. In turn, the average annual intensity of UCI is −0.3 °C. This value characterizes all seasons of the year as well. During nights, mean intensity of UCI is lower than −0.3 °C in all seasons and, for day, a bit higher than −0.3 °C likewise in each season. Maximum intensity of UCI is the highest both for the average year and winter (−4.4 °C) and the lowest in summer (−1.3 °C) (Table 2).

Taking into consideration only synoptic conditions favorable to occurrence of UHI phenomenon (i.e., without convective precipitation or direct advection of cold or warm air masses), the absolute maximum intensity of UHI (7.3 °C) occurred on 26 Jan 2010 at 22 UTC, while the maximum intensity of urban cold island (UCI) was −4.4 °C on 15 Dec 2010 at 23 UTC (average annual UCI is −0.29 °C).

3.2 The intensity of UHI under various synoptic conditions according to Niedźwiedź's circulation types for Western Poland

The synoptic circulation can be accepted as a one of the most general criteria for selection of situations conducive to the formation of the UHI and UCI. In the presented study, the types of atmospheric circulation by Niedźwiedź were accepted, assuming that the anticyclonic circulation favor the formation of a "typical" UHI or UCI and cyclonic types may be affected by errors arising from natural variability of the temperature field (Fortuniak 2003, 2006).

In the analyzed period, the cases of cyclonic and anticyclonic circulation appeared with similar frequency at the level of 48.7 and 49.2 %. During the year, cyclonic circulation prevailed in the summer and winter, and anticyclonic occurred more frequently in spring and autumn.

Among the types of cyclonic circulation, the most frequent was Bc (trough of low pressure) with annual average of 13 % and maximum in the summer of 16 %. The second most frequent cyclonic circulation was Wc with frequencies 9.4 and 12.3 %, respectively. The other types of cyclonic circulation, excluding types NWc and SWc (each about 6 % a year), occurred at frequencies up to about 3 %.

The most frequent type of anticyclonic circulation was Ka with 10.8 % average annual and maximum 13.0 % in the spring. With slightly lower annual average frequency appeared type Wa (9.0 %) which was clearly frequent in autumn (12.6 %) and in winter (10.4 %). The other anticyclonic types appear in the annual average range of 3–5.5 %.

Taking into account the types of atmospheric circulation, the frequency of the UHI and UCI in particular types of the year and seasons was calculated (Table 3). The UHI phenomena are significantly more frequent (80–90 % of all cases with particular type with atmospheric circulation) both during the year and in each season of the year then UCI one (9–20 %). The UHI occurrence in the anticyclonic types is slightly more frequent during the mean year and dominates in autumn and spring. In turn, in cyclonic types, the UHI is more frequent in summer and winter. The days with UCI phenomena are observed slightly more often during cyclonic types.

Among the anticyclonic types of circulation, the UHI is most frequent during the year in Ka type (ca. 10 %) and achieves the highest frequency in this type in spring (13.4 %). However, UHI most often occurred in cyclonic circulation of Bc type (trough of low pressure) with different directions of air flow and frontal system in the axis of trough. On average, the Bc-type frequency was about 11 % during the year and reached 14 % in summer. High frequency of this type in association with UHI seems to be surprising, because it does not fit to well known from the literature regularity of unfavorable UHI role of cyclonic circulation. The cyclonal
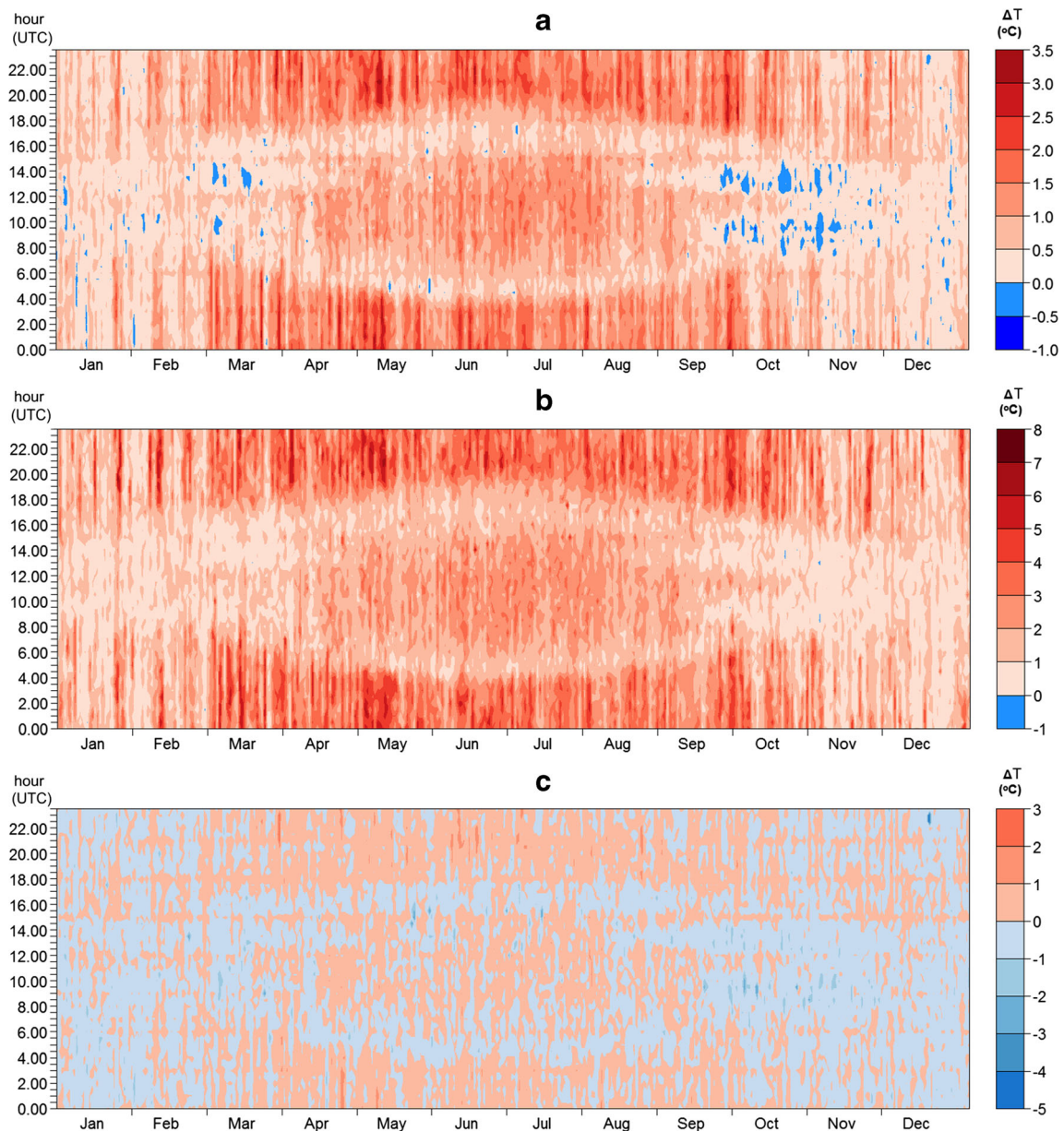
Fig. 3 Diurnal and seasonal variation of average (**a**), maximum (**b**), and minimum (**c**) air temperature differences (ΔT) between the center (Piekary) and the periphery (Ławica) of Poznań in the period April 2008–August 2013

Table 2 Seasonal and annual statistics of UHI (°C) and UCI (°C) in Poznań in the period April 2008–August 2013

	UHI				UCI			
	24 h	Night	Day	Max	24 h	Night	Day	Min
Spring	1.17	1.53	0.89	6.67	−0.3	−0.26	−0.32	−1.74
Summer	1.24	1.56	1.06	6.22	−0.29	−0.25	−0.31	−1.31
Autumn	0.92	1.09	0.63	6.12	−0.3	−0.25	−0.31	−1.92
Winter	0.67	0.73	0.55	7.32	−0.26	−0.26	−0.27	−4.41
year	1.02	1.19	0.86	7.32	−0.29	−0.26	−0.31	−4.41

The daytime and nighttime were established on the basis of sunrise and sunset for Poznań

character of the Bc type gives a relatively narrow, elongated region of low barometric pressure between two areas of higher pressure; hence, many situations classified as Bc type could be actually the anticyclonic ones favorable to UHI for Poznań.

Diurnal and seasonal variations of averaged and maximum values of ΔT separately for the types of cyclonic and anticyclonic circulation are shown in Figs. 4 and 5.

In each of the figures can be seen already described circadian rhythm of the UHI, although here much more pronounced in the anticyclonic circulation types. During those types, the ΔT intensity reaches much higher values including absolute maximum of all the reporting period (7.3 °C). In turn, during the cyclonic circulation, ΔT values are significantly

Table 3 Relative frequency (%) of urban heat island (UHI) and urban cold island (UCI) in types of atmospheric circulation in Poznań (April 2008–August 2013)

Number	Type	Spring		Summer		Autumn		Winter		Year	
		UHI	UCI	UHI	UCI	UHI	UCI	UHI	UCI	UHI	UCI
1	Na	4.2	0.5	3.5	0.1	1.8	0.2	3.2	0.2	3.2	0.2
2	NEa	4.7	0.5	4.5	0.3	2.2	0.2	0.9	0.0	3.1	0.2
3	Ea	5.6	0.5	3.9	0.4	2.9	0.6	5.8	0.8	4.5	0.6
4	SEa	5.4	0.8	2.8	0.3	4.1	1.3	4.6	2.3	4.1	1.1
5	Sa	1.7	0.5	1.7	0.3	3.4	1.6	1.1	0.5	2.0	0.7
6	SWa	1.5	0.5	2.3	0.4	5.2	1.9	1.4	0.5	2.6	0.8
7	Wa	5.6	0.7	6.3	0.6	*11.1*	2.3	*8.4*	2.0	7.8	1.4
8	NW	6.2	0.5	5.9	0.3	3.3	0.3	4.7	0.4	5.1	0.4
9	Ca	0.2	0.0	1.4	0.0	1.0	0.1	0.2	0.0	0.7	0.1
10	Ka	*13.4*	1.3	9.9	0.8	9.2	1.4	6.6	0.9	9.8	1.1
11	Nc	2.9	0.3	4.0	0.4	0.9	0.1	2.8	0.3	2.7	0.3
12	NEc	2.6	0.3	1.1	0.1	0.2	0.1	1.3	0.2	1.3	0.2
13	Ec	3.4	0.4	1.3	0.1	0.9	0.4	2.5	0.8	2.0	0.4
14	SEc	3.3	1.0	1.4	0.2	1.4	0.3	3.2	0.8	2.3	0.6
15	Sc	2.1	0.6	3.5	0.5	2.3	0.9	1.8	1.1	2.5	0.8
16	SWc	2.5	0.8	3.4	0.6	7.2	2.1	6.9	*2.6*	4.9	1.5
17	Wc	3.5	0.5	10.9	1.4	8.4	2.1	7.7	2.3	7.8	1.6
18	NWc	4.3	0.6	6.4	0.6	4.3	0.7	6.4	1.4	5.4	0.8
19	Cc	0.8	0.1	0.3	0.1	0.5	0.1	0.3	0.2	0.5	0.1
20	Bc	12.0	*1.9*	*14.5*	*1.5*	9.6	1.9	7.4	2.3	*11.1*	*1.8*
21	x	1.4	0.1	1.8	0.2	1.3	0.2	2.6	0.5	1.8	0.3
Total 1–21		87.5	12.5	90.9	9.1	81.4	18.6	79.7	20.3	85.2	14.8
Total 1–10	Anticyclonic	48.7	5.9	42.3	3.4	44.3	9.7	36.8	7.8	43.0	6.5
Total 11–20	Cyclonic	37.4	6.5	46.9	5.5	35.7	8.7	40.3	12.0	40.4	8.0

The highest values are indicated in italics

reduced. In the period from October to March, the typical rhythm of the average ΔT almost disappears in diurnal dynamics and it is only visible for the maximum ΔT values.

Most cases of the UCI in the warmer part of the year are related to the morning and evening hours, while in the colder part of the year occur at different times of the day. In turn, the maximum temperature differences indicate that the UCI in cyclonic circulation usually occurs in the transitional seasons.

In anticyclonic circulation types, the intensity of UHI is 1.2 °C on average (median is 0.86 °C), and the half of the cases of UHI is between 0.4 and 1.6 °C. Meanwhile, the intensity of the UHI in cases of cyclonic types is 0.8 °C on average (median is 0.64 °C) and the range for the half of UHI cases is 0.3–1.0 °C (Fig. 6). The anticyclonic circulation types Ka and Ca can be considered as particularly favorable to the UHI, especially to high intensity of the UHI cases. For these types of circulation, 99.3 % observations (excluding outliers) are in the range from 0.0 to 4.8 °C (type Ca) and from 0.0 to 4.0 °C (type Ka). In both of these circulation types in a half of the cases, the UHI intensity is also much higher than in other types of the anticyclonic circulations. In the Ca type (although it is not a frequent one because it represents

only 0.8 % of totals), the half of cases cover the range of 0.9–2.8 °C and the value of median (1.9 °C) is the highest among of all anticyclonic circulation types. For the Ka type, which occurs more frequently (10 % of days), the corresponding values are 0.6–2.3 and 1.2 °C. In comparison to the other types of anticyclonic circulation also stand out the Na and NEa types. The median in both of these types is 1.0 °C, and upper quartile is approximately 2.0 °C whereas, in other anticyclonic types, respective values achieved significantly lower level of 0.6–0.8 and 1.2–1.5 °C.

The UHI cases during the cyclonic circulation almost never exceeded 1.6 °C (maximal value without outliers), and 75 % (third quartile) of its values are below 0.8 °C (Fig. 6). Only in Bc and Sc cyclonic circulation types, third quartile of the UHI cases is higher and reaches 1.2–1.3 °C.

In cases of UCI is difficult to identify the types particularly favorable to this phenomena. Relatively small differences in the statistics of the various types indicate that the UCI can occur with a similar intensity in most types of anticyclonic and cyclonic circulations and usually not exceeding −0.4 °C (Fig. 6).

Figure 7 shows the seasonal pattern of UHI mean values in particular types of atmospheric circulation.
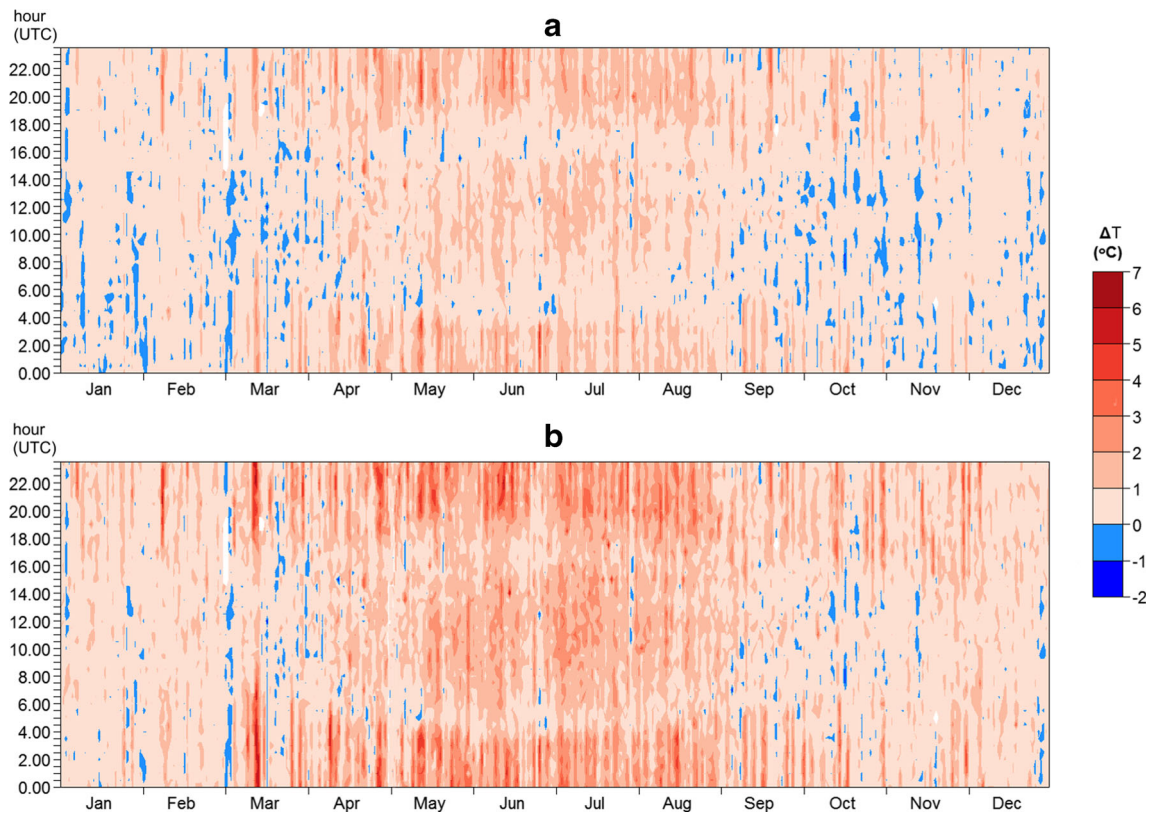
Fig. 4 Diurnal and seasonal variation of average (**a**) and maximum (**b**) air temperature differences (ΔT) between the center (Piekary) and the periphery (Ławica) of Poznań in cyclonic types of atmospheric circulation in the period April 2008–August 2013
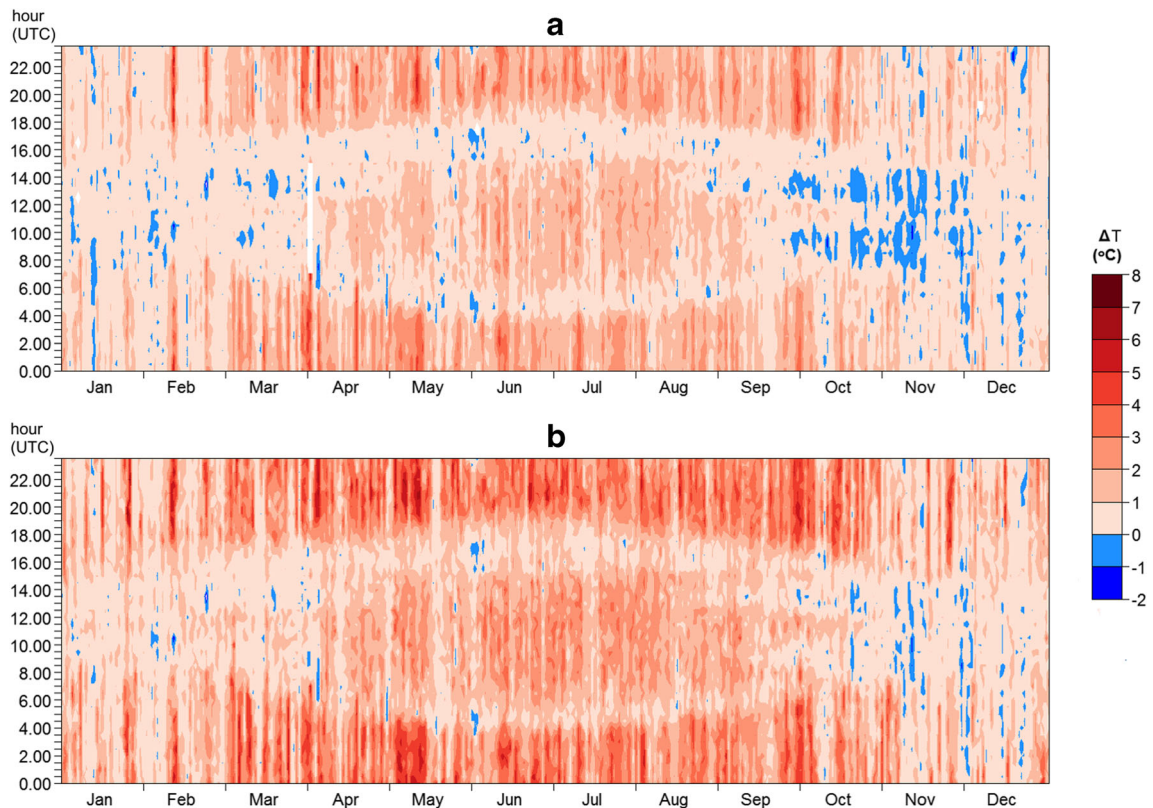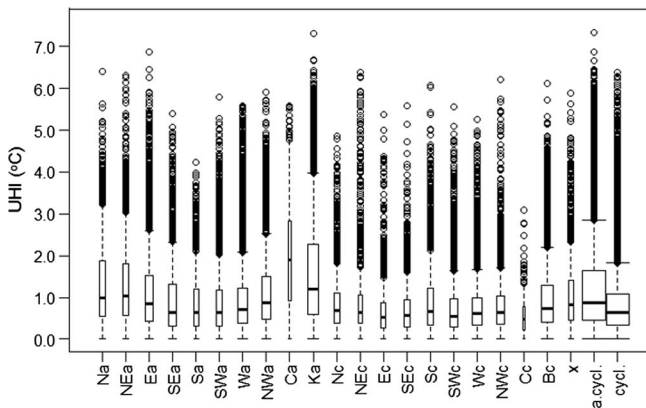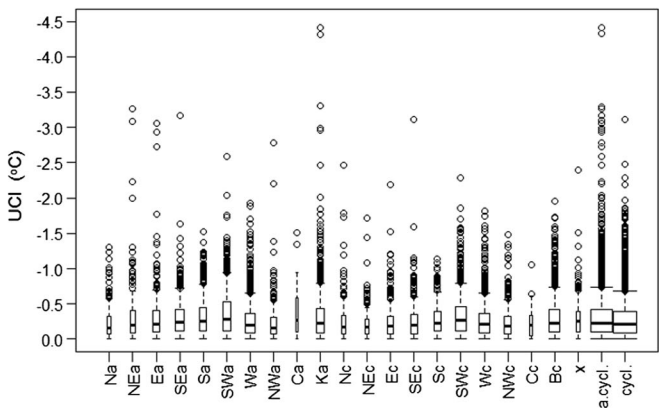

Fig. 5 Diurnal and seasonal variation of average (**a**) and maximum (**b**) air temperature differences (ΔT) between the center (Piekary) and the periphery (Ławica) of Poznań in cyclonic types of atmospheric circulation in the period April 2008–August 2013

Fig. 6 Box-and-whisker plots of UHI and UCI statistics in the period of April 2008–August 2013 in particular atmospheric circulation types of Niedźwiedź. Middle values denote medians, the *box* extends to the Q1 (first quartile) and Q3 (third quartile), and the *whiskers* show the range

(99.3 %): the *upper whisker* shows Q3+1.5∗IQR (the interquartile range), the lower shows Q1−1.5∗IQR. The *circles* represent outliers. The box widths are proportional to the square roots of the number of observations in the groups

Among four seasons, mean UHI intensity reaches a maximum in anticyclonic types in summer (median is 1.23 °C and 50 % of values range from about 0.7 to 2.0 °C). In spring season, adequate values are lower (1.0, 0.5, and 1.4 °C). In autumn, the intensity of UHI in anticyclonic types of circulation is still evidently higher than in the cyclonic types, whereas in winter, the UHI intensity in cyclonic and anticyclonic circulation types is considerably smaller.

Two types of anticyclonic circulation (Ka, Ca) stand out from all types with a significantly higher median and distribution of UHI intensity cases, especially in spring and autumn. The median value of type Ca in these times of the year is 2.1 °C, while in summer, it is slightly lower (1.9 °C), but it exceeds all other values anyway. In addition, in the summer, the UHI intensity increases in almost all types of anticyclonic circulations. For the types with the highest values of UHI can be included Na, NEa, and SEa types as well.
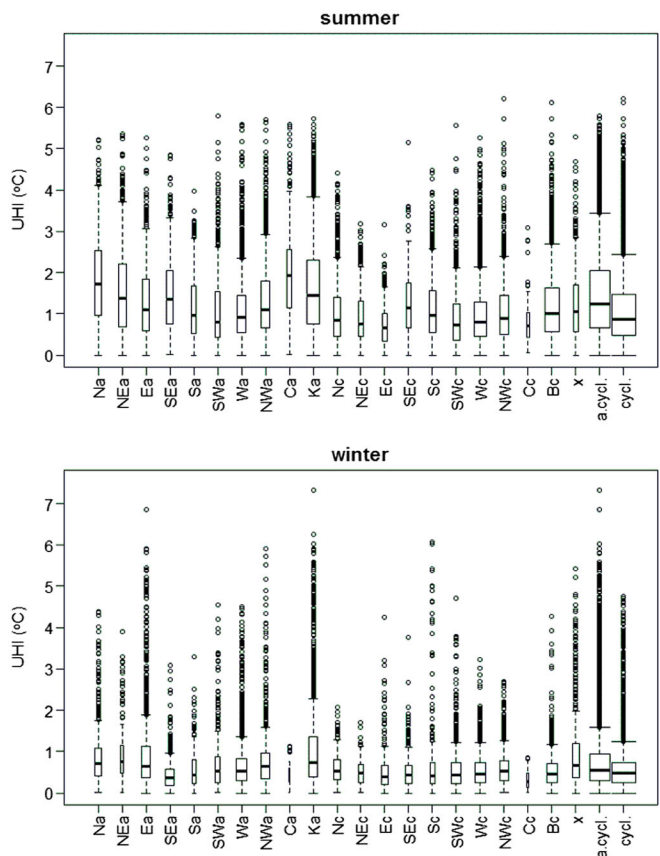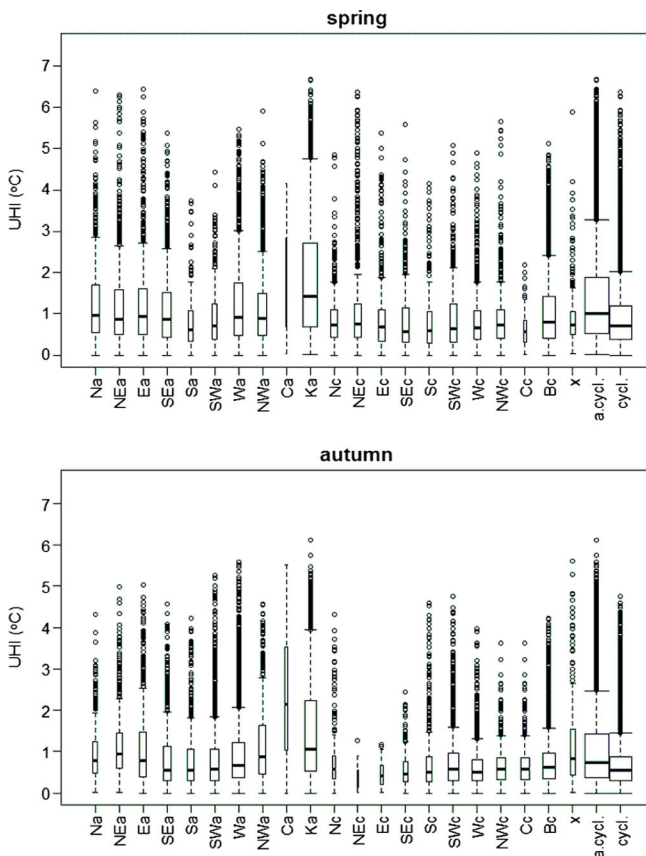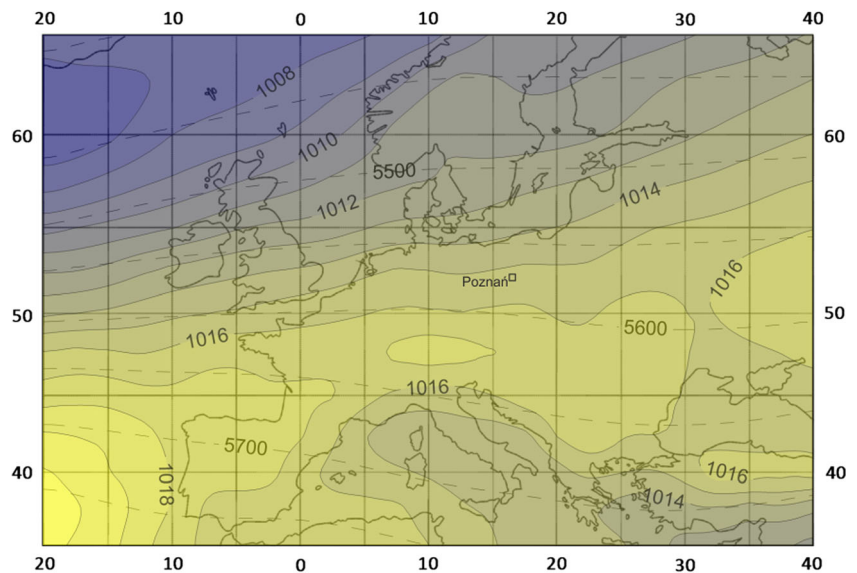

Fig. 7 Box-and-whisker plots of UHI statistics in seasons in particular circulation types of Niedźwiedź. Detailed description in the caption to Fig. 6

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Fig. 8 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) in the period April 2008–August 2013

Average intensity of UCI in particular types of atmospheric circulation is changed slightly in the different seasons (the most values are about −0.2 °C); moreover, it is impossible to point out in particular seasons of the year the UCI favorable types of circulation where the frequency of the phenomenon was significantly higher. Therefore, this problem is not shown in the figure and skipped in detailed analysis.

3.3 Synoptic situations causing UHI and UCI phenomenon by NCEP/NCAR Reanalysis

The mean distribution of SLP shows that almost all territory of Europe covers high-pressure area which forms Azores High or wedge of ridge of the high with pressure at the center of more than 1016 hPa. Only Scandinavia and middle or southern-east part of the Mediterranean region encompass low-pressure systems. The 500-hPa isobaric area is situated at a height ranging

from about 5400 m above the North Atlantic in neighborhood Iceland to more than 5750 m in the Azores High (Fig. 8).

Further in the study, we have presented composite maps of anomalies and average distribution of pressure at sea level (SLP) and the height of location of the 500-hPa isobaric surface for previously distinguished groups of days with extreme intensity values of the UCI and UHI.

The UCI phenomenon with temperature values lower or equal to −3 °C in the center of a municipal area occurred only five times during the analyzed period. The average composite maps constructed for the analyzed group of days show a high-pressure system with a center over the Bay of Riga in the Baltic Sea. The system, with a pressure in its center in excess of 1023 hPa, covers the Baltic Sea together with Scandinavia, as well as significant areas of Western, Central, and Eastern Europe, including Poland. The air pressure above Poland is about 6 hPa larger, and the 500-hPa geopotential height is
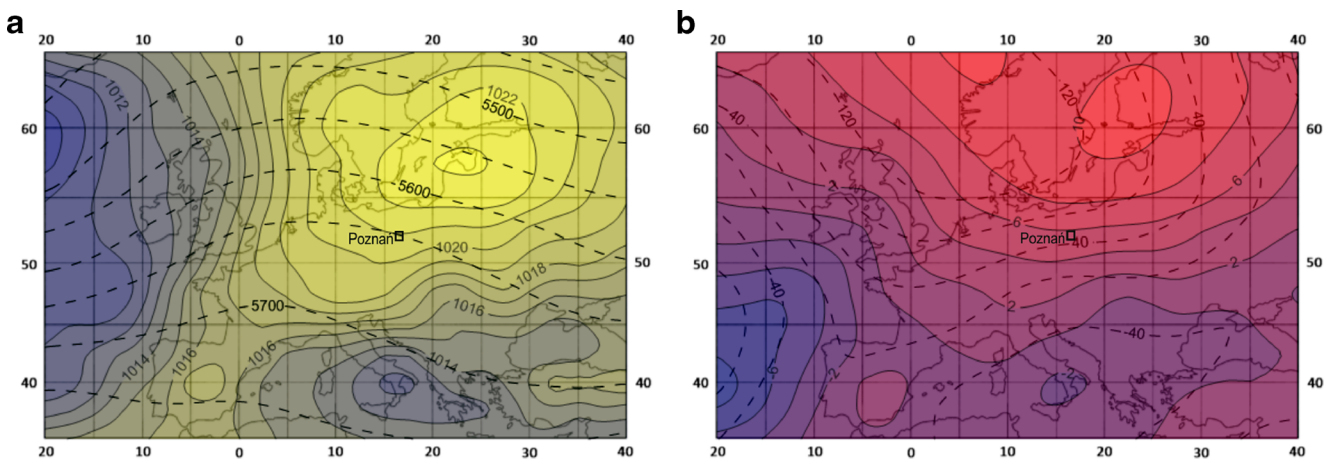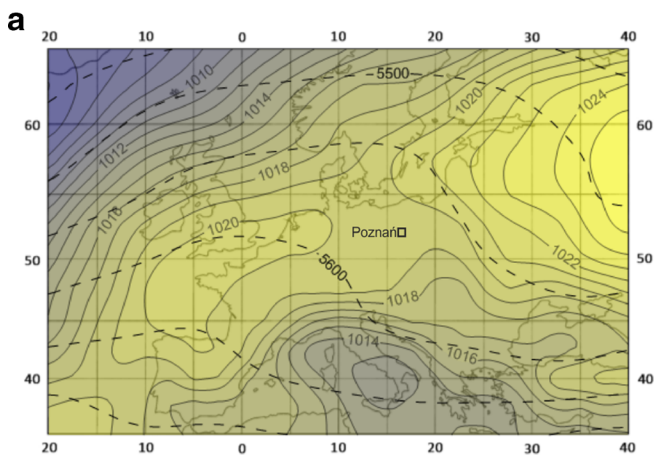

Fig. 9 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days with cooler city center in Poznań in comparison to the reference station (UCI≤−3 °C) (**a**) and its anomalies

of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013

Fig. 10 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days with cooler city center in Poznań in comparison to the reference station (−3 °C<UCI≤−2 °C) (**a**) and its
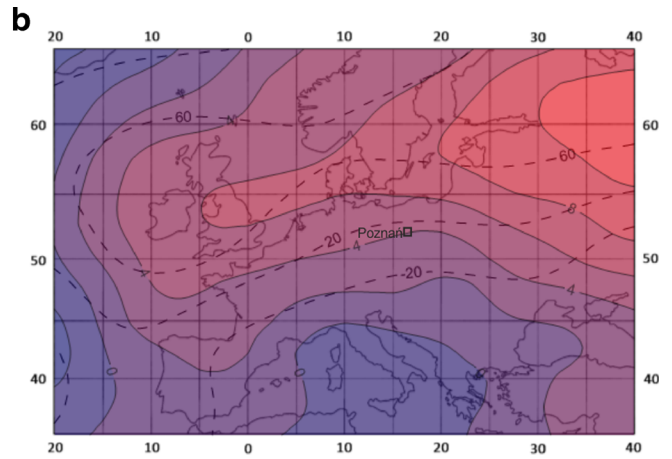
anomalies of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013

situated approximately 50 m higher than in average conditions (Fig. 9a, b).

During days from the second group (−3 °C<UCI≤−2 °C), the area of Poland was covered by a high-pressure wedge, with the center of the high located over northern Russia. In this time, a second—albeit weaker—high-pressure center formed over Western Europe. The stronger high-pressure system together with the low from the central part of the Mediterranean Sea generated an influx of warm air from southwestern Europe toward Central Europe, including over the area of Poland. This is supported, among others, by the greater about 4-hPa air pressure and approximately 20-m greater height of location of the 500-hPa isobaric surface above Poland in relation to the average situation for the entire analyzed period (Fig. 10a, b).

During days from the third group (−2 °C<UCI≤−1 °C), the average baric situation over Europe was very similar to the average for the entire analyzed period. We may, however,

observe that in days from the analyzed group, the pressure in high-pressure systems is about 2 hPa greater, while the 500-hPa isobaric surface is located about 40 m higher than under average conditions in Poland (Fig. 11a, b).

For days with the UHI intensity in the range of 4–5 °C, the distribution of pressure over Europe resembles the average for the entire research period and is also similar to the distribution of the average typical of the third group of days with the occurrence of the cold island effect. The pressure over the area of Poland is 3 hPa greater, while the 500-hPa isobaric surface is located some 50 m higher than under average conditions (Fig. 12a, b).

When the UHI intensity is greater (5 °C<UHI≤6 °C), the area of Poland is situated in the centre of a broad high-pressure area with maximum pressure in excess of 1020 hPa (about 4 hPa grater), while the 500-hPa isobaric surface is located some 70 m higher than under average conditions in Poland (Fig. 13a, b).
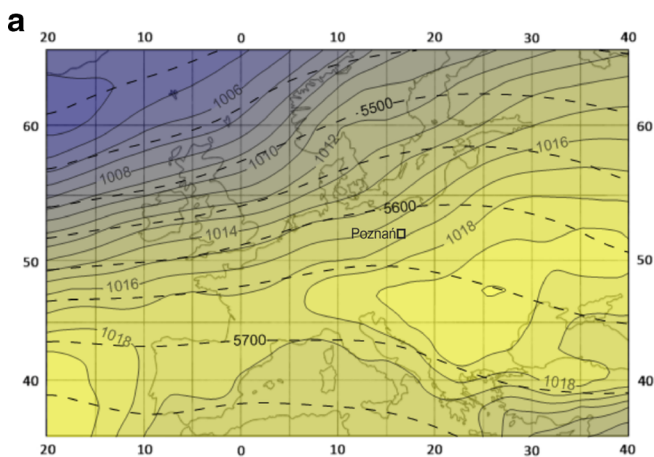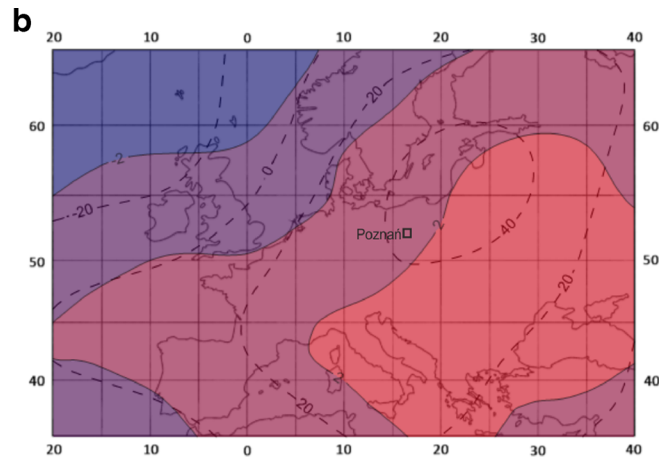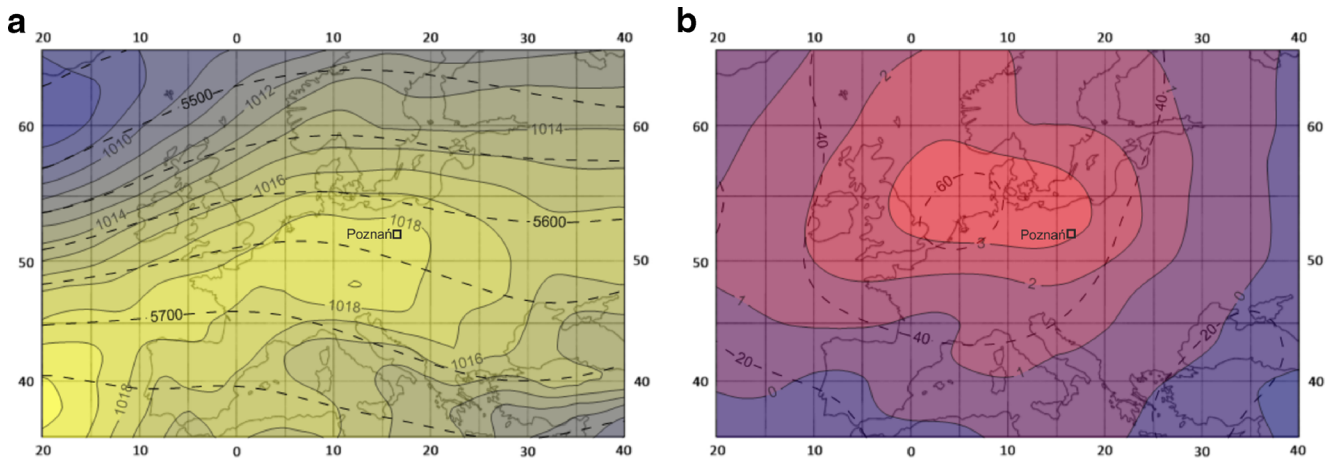

Fig. 11 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days with cooler city center in Poznań in comparison to the reference station (−2 °C < UCI ≤−1 °C) (**a**) and its

anomalies of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013

a

b

Fig. 12 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days with warmer city center in Poznań in comparison to the reference station (4 °C<UHI≤5 °C) (**a**) and its

anomalies of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013

In turn, on days with the UHI intensity greater than 6 °C, the high-pressure system impacting Poland is still stronger than in the previously analyzed group of days. Pressure in the centre of the high exceeds 1022 hPa (about 7 hPa greater than in average in Poland), while the system covers the whole of Europe, with the exception of the Mediterranean Basin (Fig. 14a, b). That high-pressure area has a low horizontal pressure gradient which additionally indicates the occurrence of windless weather. It should be pointed out that the cases of the highest UHI magnitude may appear when the drop of air temperature is additionally supported by advection of cold air masses from east and northeast direction. The shape (wave) and altitude of 500 hPa geopotential mean surface show situation when there is an advection of cold air (drop of altitude of 500 hPa on the northeastern sector of Europe). Moreover, the slope of isobaric surface from the northeast toward the southwest may indicate the advection of the eastern sector.

In turn, for the group of days in which intense UHI and UCI effect during 1 day were observed, the baric situation also presents a very broad high-pressure system with the center above southeastern Europe (Fig. 15a, b). Pressure in the center of the high exceeds 1020 hPa (4 hPa greater than in average in Poland), while the height of the 500-hPa isobaric surface is some 70 m higher than under average conditions (Fig. 11).

To recapitulate, the results obtained regarding the baric situation on days with varying UHI and UCI intensities allow us to state that these phenomena occur along in the case of clearly forming high-pressure systems that cover considerable parts of Europe. An increase in the intensity of air temperature differences between the city centre and the reference station becomes noticeable when the intensity of the discussed high-pressure systems increases.
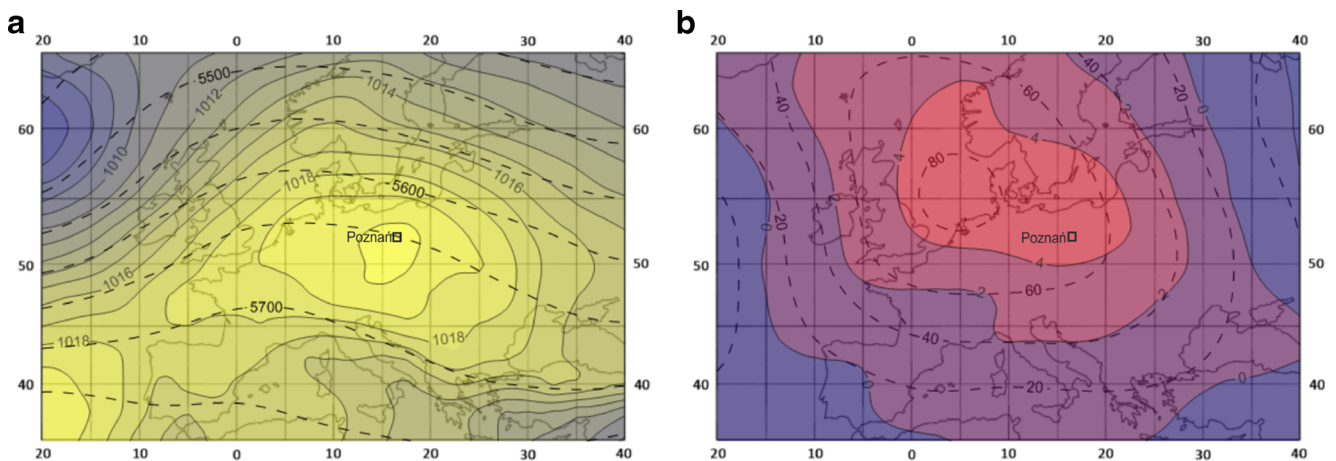
a

b

Fig. 13 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days with warmer city center in Poznań in comparison to the reference station (5 °C<UHI≤6 °C) (**a**) and its

anomalies of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013
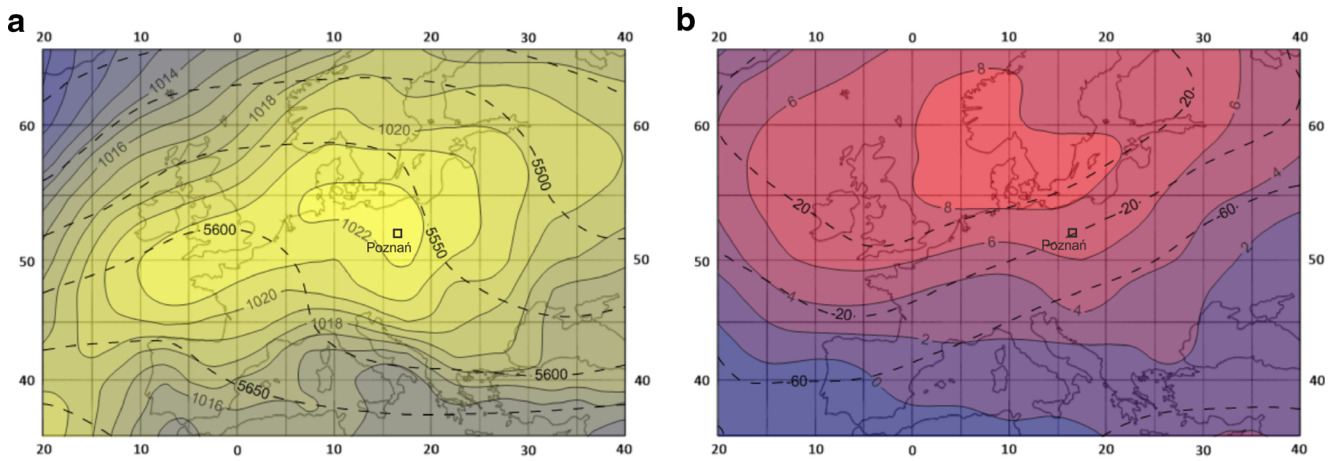
Fig. 14 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days with warmer city center in Poznań in comparison to the reference station (UHI >6 °C) (**a**) and its anomalies of

SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013

4 Conclusion and discussion

The study has analyzed UHI and UCI frequency, intensity, and influence of an atmospheric circulation on both phenomena in Poznań. The UHI phenomenon is quite common in Poznań. The cases with higher air temperature in the city center (Piekary) constitute 85.2 %. The most of them does not exceed 2 °C (70 %), and more than half of the analyzed cases are below 1 °C. In the range of 2–3 °C, it is about 7 % of all cases, over 3 °C about 4 %, and above 4 °C slightly more than 1 %. In turn, the situation with UCI phenomena appears with a frequency of 14 % a year. The vast majority of these cases do not exceed −0.5 °C.

The UHI in Poznań occurs especially in the evenings and nights, but in the daytime (with decidedly low intensity) as well. The annual average urban-rural difference is 1.0 °C, but for the day and night hours, it reaches 0.9 and

1.2 °C, respectively. Significant higher mean values (1.5–1.6 °C) reach nights in the spring and summer periods. During the winter, this value is only 0.7 °C. In spite of the higher seasonal average values of UHI appear into the warm part of the year, the absolute maximum intensity of UHI (7.3 °C) occurred in winter (26 Jan 2010 at 22 UTC). In turn, the maximum intensity of UCI was −4.4 °C on 15 Dec 2010 at 23 UTC (average annual UCI is −0.3 °C). Summer is the most favorable season for UHI formation. At this time, under the right conditions, UHI exceeds 4 °C and sometimes can reach almost 7 °C. In winter, conditions favorable to the formation of large UHI are less common but from time to time, the highest values of the UHI can also appear in this season. These results stay in agreement with similar studies conducted by Fortuniak (2003, 2006). Comparing the annual average UHI in Poznań (1.0 °C) to the other polish cities, it can be stated that the results are
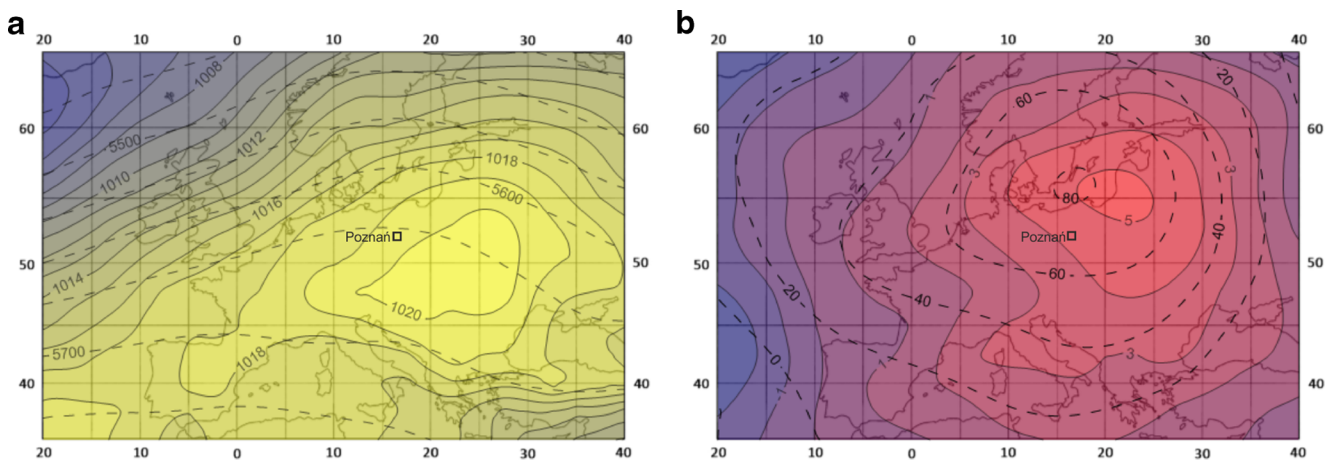

Fig. 15 Mean distribution of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed lines*) for days when the intense UHI (city center of Poznań is warmer than 4 °C in comparison to the reference station) and intense UCI (city center of Poznań is colder more than 1 °C in comparison

to the reference station) appeared during 1 day (seventh group of grouped days) (**a**) and its anomalies of SLP (*solid lines*) and geopotential height of 500 hPa (*dashed line*) (**b**). Data from the period April 2008–August 2013

quite similar to those obtained in Wrocław (Szymanowski 2004), Toruń (Wójcik and Marciniak 1984), Warszawa (Stopa-Boryczka et al. 1984), and Kraków (Lewińska et al. 1990; Bokwa 2010). It is worth emphasizing that in all the above-mentioned research as in Poznań, the UHI is described as a temperature difference between the area of the city and comparative station located at the airport situated close to the city administrative border. Obtained results confirm investigations conducted in urban areas in other countries (Sundborg 1950; Bornstein 1968; Oke 1982; Ripley et al. 1996; Philandras et al. 1999; Montavez et al. 2000; Morris et al. 2001).

It can be concluded that the UHI phenomena are significantly more frequent (80–90 % of all cases with particular type with atmospheric circulation) than the UCI one (9–20 %). The UHI occurrence in the anticyclonic types of atmospheric circulation is more frequent during the year and dominates in autumn and spring. In turn, in cyclonic types, the UHI is more frequent in summer and winter.

The intensity of UHI phenomenon in the year, as well as in each seasons, is significantly higher in the anticyclonic circulation types. During the year in anticyclonic circulation, intensity of UHI is 1.2 °C on average while in cyclonic is only 0.8 °C. The gained results confirm previous empirical works (Unwin 1980; Unger 1996; Shahgedanova et al. 1997; Morris and Simmonds 2000; Zhang et al. 2014). A high intensity of the UHI in spring, summer, and autumn is particularly associated with two types of anticyclonic circulation, Ka (anticyclonic wedge) and Ca (central anticyclonic situation without advection).

The Ka and Ca types can be considered as the favorable to strong UHI. In these types, the average UHI intensity is one of the highest in comparison to the other types of circulation. At the time with the Ca type, the average intensity of the UHI is the largest and by far exceeds the value of other types of circulation, especially in spring and autumn.

It should also be noted that in summer to the types favoring large UHI intensity belong also Na, NEa, and NWa types, which, besides high-pressure system, cause advection of cooler air from the northern sector. Statistics show that the intensity of the UHI in these types of the atmospheric circulation increases significantly during the summer season.

The cases of UCI phenomena occurred almost ever on the daytime and the most frequently in the colder part of the year together with cyclonic circulation. Among the cyclonic circulation types, the Bc, SWc, and Wc can be pointed out as favorable to UCI appearance. At the same time, it must be emphasized that UCI may also appear with a slightly lower relative frequency also in anticyclonic circulation types (e.g., SWa, Wa, Ka). This indicates the participation of additional factors besides atmospheric circulation involved in the UCI formation and much more complex reasons of this phenomenon.

Analysis of the influence of atmospheric circulation on UHI intensity on the basis of reanalysis data indicates that days with large intensity of UHI (above 4, 5, and 6 °C) are related to anticyclonic circulation. This type of circulation usually causes stronger than usual decrease of air temperature in the nighttime because of the lack or small amounts of cloud and strong radiation heating. Under these conditions between the town and surroundings areas, a large temperature gradient might be created due to the fast drop of air temperature in rural and considerably lower drop in urban area. The difference is caused by additional anthropogenic heat in the city area and heat flux of accumulated during the day in the town structure. It should be pointed out that cases of the highest UHI magnitude (above 6 °C) appear when the drop of air temperature is additionally supported by advection of cold air masses from east and northeast direction. The obtained result confirms outcome of a previous study conducted by Fortuniak (2003).

The SLP and 500-hPa geopotential maps indicate that anticyclonic circulation is also promoting the formation of strong UCI as in cases of large UHI intensity. Both composite maps based on reanalysis data and the atmospheric circulation data confirm that such cases occur in high-pressure circulation with a weakness of horizontal gradient of atmospheric pressure without advection.

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