CIRCULATION’S REQUIREMENTS OF THE URBAN HEAT ISLAND VARIATIONS
IN WARSAW

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Abstract. The results are presented concerning the study of variability of the urban heat island in Warsaw in the years 1961-2000. Urban heat island is described by the differences of temperature between three weather stations, located, respectively, in the downtown zone, the periphery, and outside of town. The direction and the rate of change in the magnitude of the differences were determined, along with their fluctuations and anomalous values. An assessment was also performed of the association between the intensity of the urban heat island and the large-scale circulation conditions, and the circulation structure was determined for the years with the anomalous magnitudes of temperature differences.

Key words: urban heat island, atmospheric circulation, Warsaw

1. INTRODUCTION

Urban heat island constitutes one of the most characteristic phenomena, accompanying urbanised areas. This phenomenon depends upon numerous factors, both the ones linked directly with the features of location of its appearance, such as density and height of urban structures, topography of the terrain, and the like, and the large-scale ones, such as the direction and nature of atmospheric circulation.

The report presents the attempt of identifying the dependence of the intensity of the urban heat island in Warsaw upon the large-scale circulation conditions, and of determining the circulation conditions, that is – the frequencies of circulation types, in the seasons featuring anomalous values of intensity of the heat island. The differences of temperature between downtown and the periphery, and between downtown and a locality outside of Warsaw were treated as the measure of intensity of the heat island. The consideration of a locality outside of town was justified by the need of disposing of the data having originated from the place, which under no conditions finds itself within the reach of the Warsaw’s heat island (this being, after all, possible in case of the town’s periphery).

2. THE SOURCE MATERIAL AND THE METHODS OF STUDY

The study was based upon the monthly averages of air temperature values from the consecutive years in the period 1961-2000, originating from three weather stations: Warsaw-Astronomical Observatory (a downtown station, surrounded by the densely built-up area, although located within a significant area of greenery), Warsaw-Okecie (an airport station, located within the south-west periphery of town), and Swider (an out-of-town station, located some 25 km to the South-east of Warsaw, in a green low-rise residential locality). The urban heat island in Warsaw was characterised through the magnitudes of the air temperature differences between the downtown station (Warsaw-Observatory) and the peripheral one (Okecie) ($\Delta t_1$), and between the downtown station and the out-of-town station (Swider) ($\Delta t_2$).

The description of the circulation conditions was made with the use of the monthly averages of the zonal and meridional circulation indicator values, determined with respect to the area limited by the parallels of 45 and 60°N, and the meridians of 10 and 30°E. Besides, the series of the seasonal and annual frequencies (numbers of days) of appearance of the particular types and macro-types of atmospheric circulation, conform to the classification of J. Litynski (Stepniewska-Podrazka, 1991, Pawlowska et al., 2000), were accounted for.

The relations of the urban heat island with the indicators and the macro-types of circulation were identified with the use of linear correlation coefficients. In order to determine the circulation conditions, which are conducive for the appearance of the seasonal and annual anomalies in the magnitudes of temperature differences, the frequencies of the circulation types in these seasons and years were compared with the respective 30-year averages (1961-1990). These years and seasons were treated as anomalous, in which the value of difference was bigger or smaller than the long-term average by more than 1.5 $\sigma$ ($\sigma$ is here the standard deviation calculated separately for the negative and positive divergences). Special attention was paid to the circulation conditions in the years with the extremely small ($\Delta t < \Delta t_{average} - 2.5\sigma_1$) and the extremely large ($\Delta t > \Delta t_{average} + 2.5\sigma_1$) differences.

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3. THE ANNUAL AND THE LONG-TERM COURSE OF DIFFERENCES

In the period 1961-2000 the annual average of the difference between the downtown and the peripheries of Warsaw ($\Delta t_1$) amounted to 0.46°C, while between downtown and the out-of-town locality ($\Delta t_2$) it amounted to 0.55°C. The season during the year, when thermal differentiation between the centre of town and its periphery is the biggest, is constituted by the months from April to July, with the average for this season amounting to 0.50°C. The smallest differences are observed in November (0.35°C). The annual course of the temperature differences between downtown and outside of town is more complex. At the end of spring and at the beginning of summer (May-July) a distinct decrease of the difference is visible (in June $\Delta t_2=0.33°C$). This fact is probably due to the influence of the local conditions — the strong warming up of the sandy bedding and the location of the station in Swider within a forest clearing. It is therefore possible that we deal, in fact, with the emergence of an “local heat island” in the case of the out-of-town station. Hence, determination of the urban heat island in Warsaw on the basis of the difference of temperatures between downtown and the station outside of town may be considered unreliable, especially during summer. The biggest thermal differentiation for this pair of stations takes place at the turn of autumn (in September $\Delta t_2 = 0.7°C$), and the smallest — apart from June — in November (0.35°C). The value of the air temperature difference between downtown and the periphery of the town ($\Delta t_1$) is the biggest in spring and in summer, while between downtown and the area outside of town ($\Delta t_2$) — in spring and in autumn.

Three sub-periods can be distinguished within the entire period in question (1961-2000), among which the air temperature differences here considered vary significantly. Thus, relatively big differences took place in the first half of the 1960s (in 1964 and 1965 the annual averages amounted to 0.7°C). Despite the rapid growth of the town in the 1970s and 1980s the air temperature differences in these decades remained at the level close to the averages for the entire period. They increased again in the 1990s, especially in the last five-year period (in 1997 the average difference attained even 0.9°C). It is in this last sub-period that the difference values have been observed exceeding any of those observed at any earlier period (Kossowska-Cezak, 2002).

The courses of the air temperature differences over the forty-year period analysed are for the particular seasons of the year similar, especially in case of $\Delta t_1$. Similarly, quite a high similarity is displayed by the courses of $\Delta t_1$ and $\Delta t_2$ (correlation coefficient values ranging between 0.62 for the autumn and 0.79 for the winter, with 0.84 for the entire year). This agreement is particularly well seen in the periods of appearance of the highest difference values: 1961-1965 and 1996-2000. Notwithstanding the periods of a distinct increase and decrease of the differences, there is, irrespective of the seasons of the year, a clear upward tendency, which in the case of differences between downtown and outside of town, $\Delta t_2$, is equal in the cool half-year and in the entire year approximately 0.05. The estimation of the trend in the changes of temperature differences on the basis of the Mann-Kendall rank method confirms the results obtained through the linear regression analysis. This trend is certainly associated with the growing area of town and with the change — especially over the last years — of the character of the urban structures in Warsaw. The increase of differences after 1995 was most probably also due to the changes having taken place in the direct surroundings of the Astronomical Observatory. The question arises whether the reasons for the change in intensity of the urban heat island in Warsaw include also, as a significant factor, atmospheric circulation. The study of dependence of the differences upon circulation was limited to the period 1961-1990, during which, as previously mentioned, the temperature differences remained at more or less the average level, although the territorial growth of Warsaw might have suggested their increase (Kossowska-Cezak, 1998).

4. RELATION BETWEEN URBAN HEAT ISLAND AND ATMOSPHERIC CIRCULATION

4.1. Urban heat island and the indicators of circulation over Central Europe

During the year the intensity of the urban heat island displays relatively weak association with the fluctuations of the zonal circulation indicator. Significant interrelations are only observed in autumn for the differences of temperature with respect to the station outside of town ($\Delta t_2$): intensification of the western circulation entails the increase of intensity of the urban heat island (Table 1). In the case of temperature differences between downtown Warsaw and its periphery ($\Delta t_1$) a definite increase of dependence upon the zonal component is observed in winter: intensification of the western circulation is accompanied by the decrease of the differences, as well as in summer and in autumn, when this dependence is positive. Most probably, the change of the sign of this dependence results both from the different influence exerted by the direction of inflow of the air masses on the air temperature in Poland, and from the very association between the differences $\Delta t$ and air temperature. The intensification of the zonal circulation ($Z_I$) brings about a significant increase of temperature in the cool half year (between October and March), and its decrease in the summer, mainly in July (Kozuchowski, Zmudzka, 2002). Although $\Delta t$ increases from winter till summer, during a given season and on the average in the year it decreases along with the increase of temperature (Kossowska-Cezak, 2002). Hence, the winter increase of temperature, linked with the intensification of the zonal circulation in this season of the year, would bring about the decrease of temperature differences, while the cooling in summer — their increase.
The meridional component of circulation displays a somewhat stronger influence on the magnitude of temperature differences. The significant interrelations between $\Delta t$ and the intensity of the meridional component take place in winter. The correlation coefficients calculated in the summer season and in autumn are also at the limit of statistical significance. Somewhat weaker associations were observed for the case of intensity of the urban heat island in Warsaw when described by the difference $\Delta t$ – for the entire year the interdependencies are statistically insignificant. A certain increase of significance of the meridional direction of inflow of the air masses can, however, be observed, in the same seasons of the year, in which it played an essential role in determination of the differences $\Delta t$.

### 4.2. The urban heat island and the macro-types of circulation

The analysis of associations between $\Delta t$ and the macro-types of circulation, distinguished with regard to the direction of the air masses, confirms the results of analysis of the dependence of the intensity displayed by the urban heat island upon the fluctuations of the zonal and meridional gradients of the air pressure over Central Europe. In the majority of cases these associations are weak or nonexistent. A significant interrelation was identified only for the case of association between the values of air temperature differences and the southern direction of inflow of the air masses in winter. The increase of frequency of advection from the southern sector contributes to the decrease of intensity of the urban heat island. This is linked with inflow of the warm air masses from this direction in winter.

No significant interdependence is observed, either, of the difference of temperature between the downtown and the periphery of Warsaw ($\Delta t$) with atmospheric circulation when we consider the macro-types classified with regard to the nature of air pressure. The significant interrelations of the air temperature difference between downtown and outside of town ($\Delta t$) with the anticyclonal macro-type appear, on the other hand, in summer and in spring, as well as for the entire year, while with the cyclonal one – in spring and in the entire year. The increased share of the anticyclonal configurations, during which cloudiness is usually smaller, is conducive to the appearance of thermal contrasts on the local scale, and thus to the increase of $\Delta t$.

Despite the generally weak associations between the $\Delta t$ and the circulation conditions, it can be observed that during the cooler part of the year a higher importance ought to be attached in the shaping of the urban heat island to the direction of inflow of the air masses, while in the warmer part of the year – to the air pressure configuration. Attention ought also to be paid to the seasonal change of the impact from some macro-types on the value of temperature differences $\Delta t$.

### 4.3. Atmospheric circulation in the seasons and years with anomalous values of $\Delta t$

In the years anomalous with respect to the values of differences, out of all the seasons of the year, the significant divergences from the long-term averages of the frequencies of appearance of the particular circulation macro-types could be noticed in winter (Fig. 1). The inflow of the air from the northern, north-eastern and eastern directions, most of all under the anticyclonal and weak-gradient situations, is conducive to the high intensity of the urban heat island in Warsaw. In the years featuring high differences $\Delta t$ the frequency of advection from the North-east is more than two times bigger than the long-term average. The limited thermal differentiation within the area of Warsaw (small $\Delta t$) occurs, on the other hand, for the increased number of days with the inflow of the air from the South-west and South under the cyclonal and weak-gradient configurations, and from the segment between S and NW under the anti-cyclonal pressure configuration. Consideration of the out-of-town station, located to the South-east of Warsaw (small $\Delta t$) indicates that emergence of such situations is enhanced by the increase of frequency of advection from South-east, South and East. The divergences of frequencies of the circulation types are, however, not so big as in the case of the positive anomalies. It is worth mentioning that the exceptionally small differences may be the evidence of both the disappearance of the heat island and of the situation, in which the weather station compared lies within the reach of the island, or (in the case of the out-of-town station) within the local heat island. This is an ambiguous situation, arising frequently and for various types of circulation.

The analysis of frequency of the circulation types in the years with anomalous $\Delta t$ confirms the seasonal change of the role played by the circulation conditions in formation of the urban heat island, and so, for instance, the
increase of frequency of advection from the eastern sector is conducive to the increase of temperature differences in winter and in spring, and to their decrease in summer and in autumn.

Figure 1. Frequency (deviations % from mean 50-years) of circulation types (after Litynski classification) in winters with anomalous values of temperature differences $\Delta t$ ( - anomalous large, - anomalous low)

Attention should be paid, though, to the fact that the seasons with abnormally low values of $\Delta t$ occurred mainly at the beginning of the 40-year period analysed, while those featuring high values of $\Delta t$ at its end, which indicates clearly that the development of the urban heat island is much more dependent upon the local factors than upon the large-scale ones, such as the circulation conditions.

5. CONCLUSIONS

- Thermal conditions depend in a significant manner upon the large-scale circulation factors. The differentiation of these conditions on the local scale, though, is subject to multiple dependencies, which may entail ambiguity of the results concerning both the intensity of the urban heat island and its associations with the factors shaping it, including atmospheric circulation.
- The choice of the weather stations accounted for in the study had a significant impact on the results obtained. The appearance of the abnormally small differences $\Delta t$ may mean the disappearance of the heat island, but also its shift and inclusion of the peripheral weather station within its reach. In the case of comparison with the out-of-town station this may also be the consequence of emergence of an own, local heat island in that location.
- The association of intensity of the urban heat island with the macro-types of circulation distinguished for the direction of inflow of the air masses is either absent or very weak. A significant interdependence was observed solely in the case of magnitude of temperature differences and the southern direction of inflow of air masses in winter. It is namely in this season of the year that the highest differentiation of the thermal features of air masses flowing in from various directions takes place.
- The increased share of the anti-cyclonal configurations, during which cloudiness is usually smaller, is conducive, especially in the warmer half-year, to the appearance of the thermal contrasts on the local scale, and thus also to the increase of $\Delta t$.
- Despite the generally weak association of $\Delta t$ with the circulation conditions it can be noted that in the cooler part of the year a higher importance in the shaping of the urban heat island ought to be attached to the direction of inflow of the air masses, while in the warmer part of the year – to the air pressure configuration. Attention should also be paid to the seasonal change of the impact from some of the macro-types of circulation on the magnitude of the temperature differences $\Delta t$.

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