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STUDIES ON URBAN CLIMATE IN POLAND

Introduction

The local modification of climate by the development of built-up areas is one of the most obvious and earliest known examples of anthropogenic climate change. Over 200 years ago, the first publication by Howard (1818) appeared showing a city centre to be clearly warmer than its surrounding area – a phenomenon now known as the "urban heat island" (UHI), and at the end of the 19th century the city's influence on other climate elements was demonstrated (Oke et al. 2017).

These local modifications are of particular importance in the light of global climate change. The "urban effect" may amplify some of the negative effects of global warming, including extreme phenomena such as heat waves or heavy rainfall and storms. Cities may thus turn out to be "ecosystems" that are extremely sensitive to climate change. On the other hand, large urban agglomerations, though they directly negatively affect the macro-scale climate only slightly, are "hot spots" on the map of global greenhouse gas emissions, and their carbon footprint is much larger than undeveloped areas of similar sizes. At the same time, there is an increase in the share of urban population in the global population – currently on in every two people lives in an urban agglomeration, and by the middle of this century it will probably be about two in every three.[1] That is why recent years have seen increasing talk of the need for spatial planning to take into account findings on the impact of buildings on local climate. Such actions can both increase cities' adaptive potential and improve their residents' quality of life, as well as reducing the negative impact that urban areas have on the environment. Climate issues, including the urban climate

[1] https://population.un.org/wup/Publications/Files/WUP2018-KeyFacts.pdf

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issues, have become a fashionable topic for press reports, and pro-climate initiatives are often cited as objectives in various urban projects. Unfortunately, the information that can be found in the mass media, and even in some "specialist" reports, shows very selective knowledge about this issue and a certain ignorance of the achievements of Polish researchers. There is a need, therefore, to draw attention to our achievements in the field of urban climate research and to recall the main findings, which, although consistent with the conclusions of scientists from other countries, also clarify the specific national conditions.

The aim of the study is to review research conducted by Polish researchers over the last hundred years or more in the field of urban climate. These works were carried out in many centres and have produced a rich literature, a full discussion of which exceeds the length constraints of a single article. Thus, focus has been placed on reviewing research conducted in larger cities and a brief description of their main results. The issue of urban air pollution has been given only a cursory treatment. This is undoubtedly the most evident characteristic of city air, and was noted even in ancient times, but in many respects it is a separate research area that requires an extensive independent study. Therefore, the focus was mainly on typical climatological research into basic meteorological elements. It should be noted that the authors of many works whose titles refer to urban climate in fact limit themselves to analysing selected climatic characteristics from just one station associated with a given urban area. And although the city's impact on the meteorological features analysed in such publications is a fact (as long as the station is actually located within a build-up area, which is not always so), the urban effect is difficult to ascertain in this case. Only comparative studies or spatial analyses can determine the impact of urban development on local climate conditions. For this reason, such works have been given somewhat more attention.

The beginnings of urban climate research in Poland

As in other countries, the first meteorological measurements and observations in Poland were mainly conducted in cities. In this sense, the beginnings of urban climate research coincide with the beginning of meteorological measurements. Nonetheless, these activities did not aim to understand the typical climate features of urbanised areas, but were mainly used to identify the climate conditions of the region in which the city was located. An example of this type of study is the 1828 *Meteorographical card of the capital of the Kingdom of Poland* [*Karta meteorograficzna stolicy Królestwa Polskiego*] by Jastrzębowski prepared mainly based on measurements conducted by Magier and Ruchacz in 1803-1828. Measurements in Warsaw had previously been made by Bończa-Bystrzycki (1779-1799), and as part of the Florentine network (1655) (Przybylak 2010;

Kossowska-Cezak, Wawer 2014). In Kraków, however, temperature observations have been conducted since 1792 – they were initiated by Jan Śniadecki at the Astronomical Observatory (Trepińska, Kowanetz 1997; Trepińska 2007). In the latter half of the 19th century, studies appeared on the city's temperature variability (Wierzbicki 1871; Karliński 1876, 1898; Kuczyński 1884) and wind speed (Karliński 1877). In Gdańsk, systematic meteorological measurements and observations began back in 1739 (Miętus et al. 1994; Filipiak, Miętus 2019). In Toruń, the first regular measurements were carried out in 1740-1767, and then from the latter half of the 19th century (Pawłowski 1918; Pospieszyńska, Przybylak 2018). In Wrocław, the earliest data is from 1710 (Przybylak 2010), but systematic instrumental measurements began in 1791 (Pyka 2003); meanwhile, in Szczecin, research began in 1836 (Miętus et al. 1994). Later, permanent measuring stations were established in other major Polish cities, for example in Lublin in 1869 (Kaszewski 2019) and Łódź in 1903 (Kłysik et al. 1995a).

The aforementioned *Meteorographical card* ... was in essence an addition to Jastrzębowski's dissertation *On air varieties and physical seasons in our climate [O odmianach powietrza i o fizycznych porach roku w naszym klimacie]* submitted in 1828, and published twelve years later under a different title (Jastrzębowski 1841; Kossowska-Cezak, Osowiec 2017). The author mentions in it the temperature corrections introduced by Magier, because "the temperature evoked by the thermometer differed because of its location within the city from the temperature in the suburbs of Warsaw, especially in winter by 1 to 3 degrees". At the same time, Jastrzębowski suggests that the amendments "were especially exaggerated in winter," although he justifies the need for them by the fact that "observations recorded in diaries are meant to mark the temperature not in the middle of the city, but in the suburbs, in the great squares and in Warsaw's gardens, which is slightly different again from the temperature in the open field". The above statements put Polish climatologists among the pioneers of urban climate research, and although the city's thermal effect was not as prominent here as in Howard's (1818) work, they undoubtedly testify that as early as the beginning of the 19th century Polish researchers were aware of the impact of urban buildings on temperature and made attempts to quantify the phenomenon.

A more accurate assessment of Warsaw's impact on air temperature can be found in a much later work by Gorczyński and Kosinska (1916), where the authors state: "As we know from searches, e.g. Renou for Paris, Lamont for Munich, Hann for Vienna and Harden Hamberg for Stockholm, Wild for Petrograd, and Gorczyński for Warsaw, city centre monthly average temperatures are up to 1½° higher in summer (around ½° in winter) than in an exposed spaces beyond the city limits; over the course of the day, the greatest positive temperature difference is seen in the urban environment in early morning and evening hours. In the afternoon, not only is the temperature in the city not higher, but, as the example of Warsaw shows, it is (especially in spring) cooler in the city than outside its borders." Therefore, attention was paid not only to the urban heat island, but also to what is known as the "cool lake". The separation of thermal conditions in the city in terms of ground-level air was also emphasised by Gumiński (1930), though citing 1925 data from Munich. In other early Polish climatological studies, Merecki (1915) noted the drop in total annual sunshine duration resulting from the increased dust and soot content in the air of major cities; Gorczyński analysed sunshine duration in Kraków (Gorczyński 1910), Warsaw, Gdańsk and Gdynia (Gorczyński 1939), and Dziewulski (1917) in Kraków, Zakopane and Lviv. It should also be mentioned that in the early 20th century and the interwar period, many Polish cities had networks and measuring stations at various times (Rojecki 1956) that made possible later analyses of the impact of urban development on local climate conditions (e.g. Kłysik, Fortuniak 1998, 1999).

Post-war and contemporary climate research in selected Polish cities

In the early post-war years, there was practically no significant research aimed at understanding the specific characteristics of urban climate, although information on patterns in meteorological features in large urban centres was an important part of research into the climate of larger areas (e.g. Gumiński 1950; Stenz 1952). The first comparative studies of urban versus rural areas includes an analysis of selected features of Lublin's heat and precipitation conditions presented by Paszyński (1957). Lublin is also the object of one of the first post-war urban climate studies done for urban planning purposes (Zinkiewicz, Warakomski 1960). The issues of taking a specific local climate into account when planning changes to the city's structure were also addressed by a large research project led by Zych and Różański in Łódź in 1955-1959 (Tarajkowska, Zawadzka 1984). The resulting studies (Różański 1959; Różański et al. 1961; Zych 1961) became a model for many later analyses. In the early 1960s urban climatology developed quite rapidly, and the issue became important in the work of most research institutions occupied with atmosphere research.

The achievements of Warsaw scientific facilities in urban climate, in its broad sense, are very abundant, and thus extremely difficult to present as a synthesis. Typically climatological issues have long been major areas of interest for climatologists at, among others, the Climatology Department of the University of Warsaw, the Institute of Geography and Spatial Development of the Polish Academy of Sciences, the Institute of Meteorology and Water Management – National Research Institute, and the Department of Meteorology and Climatology at the Warsaw University of Life Sciences (SGGW). We should also remember other entities that address related issues, e.g. air purity status, air pollution, atmospheric aerosol over the city, planning issues and numerical modelling. The intensity of research into the climate of Warsaw is evidenced by the fact that the University of Warsaw's Department of Climatology alone has produced over one hundred and fifty master's theses on the topic the years 1952-2010 (Stopa-Boryczka et al. 2010). Over the last few decades, Warsaw research teams have set up their own measurement networks and points, both specialised ones and ones providing information on the status of basic meteorological features. Numerous field studies have also been made. However, the results of these measurements have relatively rarely been presented as collective studies.

One of the first post-war works on the impact of urban development on the climate of Warsaw is the study by Kaczorowska (1967) on the spatial distribution of precipitation in the period 1956-1960. A little later, Kossowska's doctoral dissertation (1970) was published; it is considered to be the first monograph on Warsaw's climate (Żmudzka 2019) and although the author does not yet use the term "urban heat island", she draws attention to, among other things, temperature variation in the city and the circulation and weather conditions that determine it. In later years, the Warsaw urban heat island was the subject of numerous studies, which were undertaken by, among others, Stopa-Boryczka et al. (1984, 1991, 1994, 2001, 2003), Wawer (1995, 1999), Kozłowska-Szczęsna et al. (1996, 2001), Błażejczyk (2002) and Błażejczyk et al. (2014, 2016), as well as Lorenc and Mazur (2003). These were often monographs and collective publications devoted exclusively to the UHI phenomenon (Błażejczyk et al. 2014) or to the comprehensive analysis of Warsaw's climate, including various meteorological elements (e.g. Kozłowska-Szczęsna et al. 1996; Lorenc, Mazur 2003; Stopa-Boryczka 2003; Stopa-Boryczka et al. 2010). These bound publications – and numerous publications a detailed overview of which exceeds the scope of this study – include analyses of the impact of Warsaw's urban buildings on most of the basic meteorological elements.

Contemporary trends in Warsaw climate research, in addition to classic studies on the diversity of local climate, its weather and circulation conditions, and long-term changes, include a number of problems of a specialist or applied nature. Bioclimate issues are a very important research trend that has for many years been worked on intensively by a team of climatologists from the PAS Institute of Geography and Spatial Organisation (Kuchcik et al. 2019). In recent years, works have considered, for example, the distribution of the universal thermal climate index (e.g. Błażejczyk 2013), assessing the bioclimate of residential districts depending on the share of biologically active areas (e.g. Szulczewska et al. 2014) or the allergenicity of plant cover (e.g. Kuchcik et al. 2016). In addition, modern research directions in Warsaw include: modelling contemporary climate threats, in particular thermal ones in Warsaw (Kulesza et al. 2017); LiDAR studies of the urban boundary layer (e.g. Stachlewska et al. 2017); analysis of the surface urban heat island (Gawuć, Strużewska 2016) or numerical modelling of the climate of cities (e.g. Strużewska, Kamiński 2012; Wyszogrodzki et al. 2012; Korycki et al. 2016). It is worth remembering that the pioneering works in numerical modelling of urban climate by Sorbjan and Uliasz are connected with the Warsaw centre (Sorbjan 1978; Sorbjan, Uliasz 1982).

In Kraków, studies on the local climate have also been conducted by many research facilities, including universities (mainly the Department of Climatology of the Jagiellonian University), departments (IMGW, the Institute of Urban Development, the Institute of Spatial and Municipal Management, the Institute of Environmental Development [*Instytut Rozwoju Miast*, *Instytut Gospodarki Przestrzennej i Komunalnej*, *Instytut Kształtowania Środowiska*]) and institutions of the Polish Academy of Sciences. As in Warsaw, this has resulted in an abundant literature. Studies from the early post-war years mainly concern selected features of the Kraków environment (e.g. Morawska 1963; Hess 1967, 1974; Trepińska 1969). The extremely long measurement series from the research station belonging to the Department of Climatology of the Institute of Geography and Spatial Management of Jagiellonian University and housed in the Botanical Garden was the basis of many studies on long-term changes in selected climate elements (e.g. Twardosz 2005; Matuszko 2007, 2009; Piotrowicz 2010). It has also been used in comparative studies (e.g. Niedźwiedz et al. 1984; Drużkowskiowski; Bokwa 2010) and works on the city's potential influence in historical time series (Morawska-Horawska 1991; Kożuchowski 1995).

One of the first studies on the variability of meteorological elements (precipitation) within Kraków and in the surrounding area was conducted by Lewińska (1967). Her later studies on the climate of urban areas were summarised in a monograph on Krakow's mesoclimate (Lewińska et al. 1982). The specific topographic conditions of the city's location mean that, here, terrain has a greater impact on the course of precipitation and other meteorological elements than it does in other major cities in Poland. Consideration of the additional impact of topography on the variability of the thermal field of Kraków city led to the concept of the relief-modified urban heat island (Bokwa 2010; Bokwa et al. 2015). The exceptional location of Kraków also gave the impetus to develop research on thermal inversions over the city, the vertical range of the urban heat island, and the structure of the urban boundary layer of the atmosphere (e.g. Milata 1959; Morawska-Horawska, Cebulak 1981; Lewińska 1984; Walczewski 1984, 1994). These studies drew on empirical data from stations at various altitudes, as well as results from balloon surveys, aeroplane flights or pioneering sodar observations conducted since 1980 by the IMGW Institute of Atmospheric Remote Sensing in Kraków-Czyżyny.

The latest research issues undertaken by Kraków researchers (Bokwa 2019) include, in addition to classic studies of urban climate: attempts to accurately determine the role of topography as a major factor alongside land cover and land use in shaping the city's climate (Bokwa et al. 2015), the use of satellite data to analyse the substrate thermics of Kraków and surrounding area (Walawender 2006; Matuszko, Wojkowski 2007; Walawender et al. 2014), the use of climate models to study the mesoclimate of Kraków, and the study of isotopic characteristics and greenhouse gas fluxes over the city (Zimnoch et al. 2010, 2018).

In Łódź, urban climate is a major area of researcher interest, starting from the aforementioned works by Zych and Różański (Różański 1959; Różański et al. 1961; Zych 1961). Urban climate research intensified particularly after the Urban Meteorological Station was created in 1992 (Kłysik et al. 1995b) in the very centre of the city, and subsequently functioned until 2012. Further progress came after the automation of measurements in 1996. This made a number of comparative analyses possible using data from the Łódź-Lublinek station (which is considered as rural), mainly regarding air temperature and radiation conditions (e.g. Kłysik, Fortuniak 1998, 1999; Fortuniak 2003; Fortuniak et al. 2006; Podstawczyńska 2007). Simultaneous traverse measurements allowed the detection of a Polish national record UHI, with temperature differences between the city centre and rural areas of around 12°C (Kłysik, Fortuniak 1999). At the same time, the emission of artificial heat was estimated in Łódź (Kłysik 1996) and maps of land cover relevant to climate-forming processes above the city were drawn up (Kłysik 1998). Of note are also works on modelling of the urban climate, including the UHI (Fortuniak 2003) or radiation absorption by urban structures (Fortuniak 2008; Pawlak 2009). Activity in the field of urban climate at the Łódź centre includes cyclical *Urban climate and bioclimate* conferences (in 1984, 1992, 1997, 2007, 2015) and the holding of the *5th International Conference on Urban Climate* in 2003.

Since 2000, micrometeorological measurements have become an important aspect of urban climate research in Łódź. In cooperation with the University of Indiana, the first eddy-covariance system was launched in Łódź, enabling the measurement of turbulent sensible and latent heat fluxes (Offerle et al. 2006a, b). Since 2006, measurements of carbon dioxide flux have also been conducted (Pawlak et al. 2011), and of methane flux since 2013 (Pawlak, Fortuniak 2016). In the years 2009–12, studies on the intensity of turbulence and turbulent sensible heat flux over the city were carried out on a three-kilometre measurement path using a scintillometer (Zieliński et al. 2013, 2017, 2018). Turbulence characteristics were also analysed based on several years' data from two covariance towers (Fortuniak et al. 2013; Fortuniak, Pawlak 2015). In addition, in recent years Łódź noteworthy research has been done on meteorological determinants of radon concentrations in the urban ground-level air layer (Podstawczyńska 2013, 2016).

In Wrocław, the earliest post-war urban climate works concerns modification of the atmospheric precipitation field (Schmuck 1967; Zipser-Urbańska 1968). Meanwhile, the first comprehensive climate study of Wrocław was conducted in the early 1970s. As part of a three-year project, a network of twenty topoclimatic measuring stations was in operation at the time (Pyka 2003; Szymanowski et al. 2019). Wrocław's began engaging in detailed recognition of urban climate features in the very late 20th century. Particularly noteworthy is the effective use of GIS methods in comprehensive analyses combining data from automatic measuring stations (five automatic stations operating since 1997) with mobile measurements, allowing the modelling of the spatial distribution of meteorological elements in the city at a high spatial resolution (e.g. Dubicka, Szymanowski 2000; Dubicka et al. 2003; Szymanowski 2004). The methodology developed during these studies was also used to determine bioclimate conditions (Sikora 2008). Research into the urban atmospheric boundary layer is another important area of scientific activity of the Wrocław's climate facilities. They began with the 1984 creation of a sodar measurement station (Pyka 1988), which was progressively expanded in subsequent years, including with mobile sodar enabling the analysis of the spatial structure of inversions over the city (Netzel et al. 2012). In studying the structure of the atmospheric boundary layer above Wrocław, balloon measurements have also been used (Drzeniecka et al. 2003), as have measurements at various altitudes on the meteorological tower (Drzeniecka-Osiadacz et al. 2018) and, in recent years, surveys using a meteorological drone (Szymanowski et al. 2019). These observations made possible an empirical database for verifying the numerical parameterisation of the urban atmospheric boundary layer (Netzel et al. 2012; Kryza et al. 2015). The numerical modelling of meteorological processes and air quality is currently one of the main research currents in the climatological centre in Wrocław (Szymanowski et al. 2019). This objective employs properly optimised WRF and WRF-Chem models, and the latest works, in addition to modelling typical air quality indicators such as suspended dust (Werner et al. 2015) or ozone (Wałaszek et al. 2014), also include interdisciplinary issues, e.g. modelling the transport, concentrations and emission of pollen (Bilińska et al. 2017).

As already mentioned, one of Poland's first post-war studies on the city's impact on local climate conditions concerned Lublin (Paszyński 1957; Zinkiewicz, Warakomski 1960). In later years, however, most of the works describing urban climate focused around the temporal variability of individual meteorological elements and bioclimatic indicators and their circulation conditions (e.g. Michna 1955; Michałowski 1962; Kossowski 1970, 1973; Badach et al. 1985; Warakomski 1999; Gluza 2000; Kaszewski, Bilik 2015; Nowosad 2012). A little later, comparative studies of Lublin centre versus its rural areas appeared (e.g. Filipiuk et al. 1998; Kaszewski, Siwek 1998; Nowosad, Bartoszek 2007), as did works on climate and bioclimatic diversity in the city (Gluza, Kaszewski 1984; Mrugała et al. 1991; Dobek, Gawrysiak 2009; Dobek et al. 2013). Today, Lublin climatologists focus largely on applied issues (Kaszewski 2019), e.g. on the role of dry valleys in shaping thermal and humidity conditions in Lublin (Kaszewski et al. 2014) or on assessing the impact of roadside greenery on the urban microclimates (Kaszewski 2017).

The urban climate research by Toruń's Nicolaus Copernicus University team falls into two main periods: 1981-1993, when a network of eight manual measuring stations operated in the city (Wójcik, Marciniak 2007), allowing, among others, evaluation of the differentiation of thermal conditions in the city (Wójcik, Marciniak 1984); and 2011-present (Przybylak, Uscka-Kowalkowska 2019), when a network of twenty-seven automatic measuring points was created (twenty-four new and three previously operating) as part of a project aimed at understanding the diversity of Toruń's local climates. The works created at that time concern, among other things, the spatial differentiation of temperature (Przybylak et al. 2017), air humidity (Uscka-Kowalkowska et al. 2014), wind direction and speed (Strzyżewski et al. 2015), biometeorological conditions (Arażny et al. 2015, 2016) and solar radiation (Kejna et al. 2014) in selected years.

In Poznań, the differentiation of selected meteorological elements for 1962-1964 was analysed by Szczerbacki (1968) and then by a team led by Koczorowska (1995) on the basis of a short, one-year measurement series from 1992-1993. In the early 20th century, preliminary comparative studies of thermal contrasts between the city and its rural surroundings were carried out by Bednorz (2003). However, until 2008, when the municipal measurement network of the Adam Mickiewicz University's Climatology Department was established, Poznań climate studies focussed predominantly on the characteristics of meteorological elements based on data from the Poznań-Ławica airport station (e.g. Woś 1992; Tamulewicz 1996; Kolendowicz 1999; Szyga- Pluta 2003). It is only with the data from the newly created network that detailed *UHI* analyses have been created in recent years (Nowak 2009; Busiakiewicz 2011; Półrolniczak et al. 2017, 2018, 2019). Attempts have also been made to use surface *UHI* images from satellite data to identify in detail the distribution of the air temperature field inside Poznań (Majkowska et al. 2017).

The first post-war works from the Gdańsk–Gdynia–Sopot Tri-City concerned sunshine duration in Gdynia (Lechowicz-April 1961). A wider study of the diversity of climatic conditions in this city was conducted by Trapp (1978). In later years he and his team described the climatic conditions (Trapp et al. 1987) and bioclimatic conditions (Nurek et al. 1992) of the Gdańsk agglomeration. At the same time, attention was paid to the impact of the sea and the particular topography, which modify how buildings influence thermal conditions (Korzeniewski 1994). At the end of the 20th century, most research in the Tri-City focused on determining the meteorological conditions of the agglomeration's air-quality status (Wyszkowski 1994; Wyszkowski, Mysiak 1995). In recent years, much attention has been devoted to reconstructing Gdańsk's climate conditions (Miętus 1998; Miętus et al. 2007), taking into account anthropopressure (Miętus, Filipiak 2001) and bioclimatic issues (Owczarek 2003, 2012).

In addition to the larger urban centres listed above, research into selected urban climate elements has also been done in many other cities, although these works were not as comprehensive. In particular, the bioclimates of many Polish spa towns were characterised (e.g. Jankowiak, Parczewski 1978; Kozłowska-

Szczęsna 2000; Kozłowska-Szczęsna et al. 2002). The influence of buildings in modifying local climate conditions has also been analysed in terms of bioclimatic conditions in studies in other cities, e.g. in Częstochowa (Tarajkowska 1971), Kielce (Żarnowiecki 2002) and Szczecin (Czarnecka et al. 2011). One interesting approach to the research into the complex impact of the city on climate conditions is the dendrochronological research conducted in Szczecin (Cedro, Nowak 2013). Typical meteorological elements were also analyzed in many cities, including the thermal conditions of Bydgoszcz (Dudek et al. 2008), anemometric conditions of Szczecin (Nidzgorska-Lencewicz, Czarnecka 2011) and topoclimatic differentiation of Katowice (Radosz 2010) and Sosnowiec (Radosz 2007). The unique measuring possibilities offered by the tall building of the Faculty of Earth Sciences at the University of Silesia in Sosnowiec were used to analyse thermal inversions over the city and their relationship with atmospheric circulation and air pollution (Bil 2000; Caputa et al. 2009; Widawski 2015).

Selected local climate features in Polish cities

In urban climate research, aside from the problem of air pollution, most attention has probably been given to the urban heat island phenomenon. Both in Poland and abroad, it is most often analysed in relation to air temperature measured among urban buildings at the standard (or similar) Stevenson screen height. The literature refer to this as the canopy-layer urban heat island (Oke et al. 2017), although generally, when speaking of the urban heat island, it this type of *UHI* that is often implicitly assumed (this convention has also been adopted herein, though hereinafter the designation UHI_{CL} will be used). Remote-sensing methods, mainly satellite, make it possible to study the "surface urban heat island" (UHI_{Surf}), which determines the differentiation in the radiative temperature of urban surfaces. However, for studies concerning the thermal structure of the air above the city, we speak of the "boundary-layer urban heat island" (UHI_{UBL}). Oke et al. (2017) distinguish the "subsurface urban heat island", which relates to the temperature of deeper soil soil and the city's modification of the geothermal gradient, but there are very few works on this issue (none in Poland).

In light of average annual urban heat island values (UHI_{CL}) being relatively low, and urban–rural temperature differences (ΔT_{u-r}) for major Polish cities rarely exceed one degree (Przybylak et al. 2017). However, in exceptionally favourable weather conditions these differences ($\Delta T_{u-r(max)}$) may even exceed 10°C. The largest recorded urban-rural thermal contrasts for Polish cities exceed 11°C in Łódź (Kłysik, Fortuniak 1999), and are almost 11°C in Warsaw (10.8°C: Wawer, 1995), 10°C in Kraków (9.9°C: Bokwa 2010), 9°C in Wrocław (Dubicki et al. 2002), 8°C in Lublin (8.0°C: Kaszewski, Siwek 1998) and 7°C in both Bydgoszcz (Dudek et al. 2008) and Poznań (Półrolniczak et al. 2017). These values are within the range

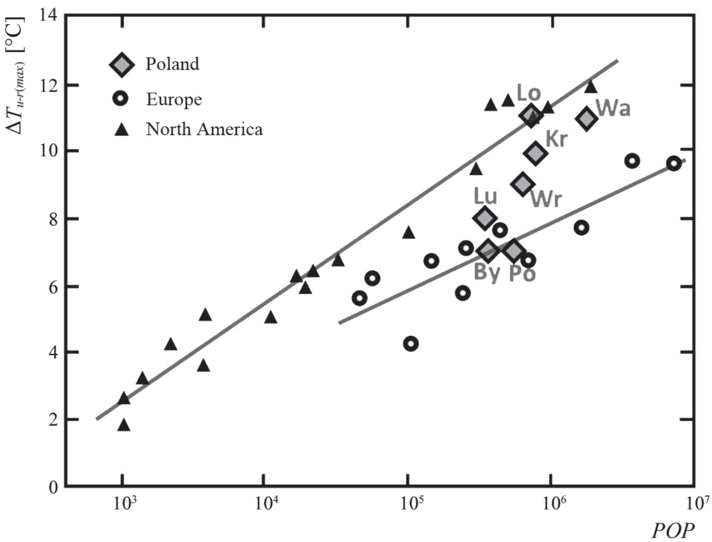

Fig. 1. The highest observed urban–rural temperature differences ($\Delta T_{u\text{-}r(max)}$]) as a function of population (*POP*) for Polish, European and North American cities (after Oke 1973, modified)

recorded for other cities, although the dependence of $\Delta T_{u-r(max)}$ on number of inhabitants is weaker than for European cities in general (Fig. 1). The exceptionally high value in Łódź may be partly due to the cited extreme $\Delta T_{u-r(max)}$ was taken from mobile measurements, which can determine the temperature field along the route to a high degree of detail, while the results for most other stations come from fixed stations. The highest $\Delta T_{u-r(max)}$ values in Łódź for fixed measurement points are around 9°C.

It should be emphasised that the quoted values refer to extremely rare extreme conditions, while typical urban-rural thermal contrasts, which appear at night in favourable weather conditions, reach 4-6°C in summer and 2-3°C in winter in large cities, and on average (all weather conditions) are 1-2°C in summer and 1°C or less in winter. During the day, the temperature differences are small, and sometimes temperatures can be even lower in the city centre than in rural areas. This is a manifestation of the dynamic nature of UHI_{CL} – the ΔT_{u-r} thermal contrasts start to increase rapidly at sunset, then stay relatively constant at night, to disappear rapidly after sunrise (e.g. Kaszewski, Siwek 1998; Fortuniak et al. 2006). Polish studies also confirm the dependence of UHI_{CL} on meteorological elements. The aforementioned "favourable weather conditions" are cloudless, windless nights. As wind speed and cloudiness increase, the urban heat island weakens. Because such conditions usually occur in anticyclonic situations, this circulation type favours the formation of UHI_{CL}. The above findings for Polish cities are consistent with generally accepted patterns for

UHI_{CL} (Oke 1982; Arnfield 2003; Oke et al. 2017), but Polish works have also highlighted the occasional appearance (especially with an automatic measuring network) of large differences resulting from advection factors that are not necessarily related to the urban effect (Szymanowski 2005; Fortuniak et al. 2006; Bokwa 2010; Przybylak et al. 2017).

The surface urban heat island has received less attention in the Polish literature, even though the first attempts to record ground temperature using thermal aerial photographs were made in Warsaw in the 1970s (Kraujalis 1980). Most of it consists of the works using satellite surface temperature measurements mentioned in the previous chapter. The main feature distinguishing UHI_{Surf} from UHI_{CL} is the fact that the sun's powerful heating of artificial surfaces means that UHI_{Surf} is also clearly marked during the day. Satellite images can also be used to determine the distribution of the urban temperature field in more detail when the number of measurement points is limited, while attempts to estimate the air temperature directly from radiated temperature measurements may, especially in the city, suffer from very large errors. During the day in particular, UHI_{Pow} cannot be seen as identical with UHI_{CL}.

Relatively few works address the issue of the boundary layer urban heat island (UHI_{UBL}). In Poland, UHI_{UBL} research has mainly been conducted in Kraków and Wrocław and principally related to the occurrence of thermal inversions. In both cities, inversions occur most in the cold season (about 70%), and least in summer (40-50%) (Drzeniecka, 2005; Hajto, Rozwoda, 2010). Walczewski (1994) determined the average thickness of ground inversions in Krakow at 60-200 m, while research by Lewińska (1984) determined the *UHI* range in Kraków at 100-200 m in the cold half-year and over 200 m in the warm half-year. Walczewski (2005) determined the vertical range of the mixing layer in Kraków, which also determines the altitude to which the impact of the urban surface is observed, at 800–1,000 m in the day and 300-400 m at night in the warm season and 300–600 m in the cold season.

As with thermal contrasts, the variability of the air humidity field has been analysed, although there are far fewer studies devoted to this issue. The situation is complicated by the various humidity characteristics, with relative humidity having a qualitatively different course than absolute measures of the water vapour content in the air, such as water vapour pressure, absolute humidity, specific humidity or mixing ratio. In terms of relative humidity, the city appears to be relatively dry. As with UHI_{CL}, there are clear diurnal and annual dynamics here – the largest differences (of 20-40%) can appear on fine summer nights, while increased wind speed and cloudiness reduces humidity contrasts. In winter, due to the near saturation of the air, these differences rarely exceed 10%. Also in terms of annual average, relative humidity is usually a few percent lower in the city centre than in rural areas (Gluza, Kaszewski 1984; Stopa-Boryczka 1992, 2003; Lewińska et al. 1982; Lewińska 2000; Dudek et al. 2008; Uscka-Kowalkowska et al. 2014). Humidity expressed in absolute units (all the above-mentioned absolute measures have a qualitatively similar course) is usually, in the warm season during the day, higher in rural areas than in the city, due to the higher evapotranspiration of green areas. At night, with a strong *UHI*, higher values can occur in the city. This is probably due to the more intense condensation (dew) in rural areas, which reduces the water vapour content of surface air layers. However, it should be noted that although the above patterns are taken as typical for cities at moderate latitudes (Oke et al. 2017), unlike *UHI*, favourable weather conditions (cloudless, windless nights) do not always lead to humidity contrasts developing in the way the presented diagram shows (Fortuniak et al. 2006). The complex diurnal course of differences in absolute humidity measurements between an urban and a rural area may explain the divergence (in terms of sign) in the averages of these differences in Polish cities (Stopa-Boryczka 1992, 2003; Lewińska 2000; Dudek et al. 2008; Uscka- Kowalkowska et al. 2014).

One of the first meteorological elements analysed in post-war urban climate studies was precipitation. Generally, as in most moderate climate zone cities, annual sums of precipitation are higher in Polish cities than in their surrounding areas (Kaczorowska 1967; Lewińska 1967; Schmuck 1967; Lorenc 1991; Bartnik, Marcinkowski 2015). For some areas, the area of increased precipitation was typically shifted eastward (downwind of the prevailing wind). Increased vertical movements resulting from thermal convection and surface convergence are probably the main cause of this effect. This hypothesis can be confirmed by the intensification of torrential precipitation, storms, hail, and convective cloudiness seen in urban areas, mainly downwind of the city (Lewińska 2000). Due to the effect of aerosol, the impact of air pollution on precipitation (especially intense precipitation) is more open to discussion, while the greater number of condensation nuclei in urban areas undoubtedly contributes to reducing visibility and increasing the number of mists (aerosol swelling).

Anemometric conditions are an extremely important meteorological element in terms of urban air quality. The impact of urban development on wind speed can be considered at various scales. In the case of average wind speeds in a given area, rougher terrain weakens the wind in the central districts of a city by an average of about 30-50% (or even more) relative to open rural areas (Ożga 1998; Fortuniak et al. 2006; Nidzgorska-Lencewicz, Czarnecka 2011; Strzyżewski et al. 2015). At the scale of individual architectural objects, tunnel effects or shadowing can significantly increase or decrease wind speed. It is therefore quite difficult to obtain representative measurements of direct differences in wind speed. Instead, the distribution of the surface roughness coefficient (z_0) is determined to establish the degree of wind weakening by urban development. The roughness coefficient is also used to determine what are known as "ventilation corridors", so calculating z_0 for individual buildings and their immediate surroundings, which is sometimes used for this purpose (e.g. Bochenek, Klemm 2016), is highly debatable in terms of the physical interpretation of z_0. Increased surface roughness also causes changes in wind direction and the appearance of zones of convergence forcing vertical air movements. These currents are further strengthened by convection caused by urban heat excess. Urban convection alone, however, can lead to the formation of breeze circulation in the case of stillness or weak wind at the synoptic scale. In such situations, the wind speed can be higher in the city than in rural areas (Siedlecki 2003; Fortuniak et al. 2006). The second potential cause of higher wind speeds in the city is turbulent momentum transport resulting from turbulence being increased by urban buildings (roughness) and the *UHI* (reduced stability).

Polish research has given much attention to the city's influence on solar conditions since the beginning of instrumental research (Merecki 1915; Gorczyński 1910, 1939; Stenz 1922). Air pollution in urban areas modifies virtually all components of the radiation balance. In the short-wave band it is the main reason for the reduction (by approx. 10-15%) of the transparency coefficient (Paszyński 1959; Dziewulska-Łosiowa 1962; Krawczyk 1968; Hess et al. 1980; Olecki 1992). Decreased transparency and increased cloudiness also reduce the intensity of direct and global solar radiation, as well as sunshine duration. In the case of sunshine duration, these losses are most often estimated at 5-15% (Kuczmarski 1982; Morawska-Horawska 1984; Marciniak, Wójcik 1991; Matuszko 2009). The sums of global solar radiation are on average 5-8% lower in the city centre than in rural areas (Hess et al. 1980; Kozłowska-Szczęsna, Podogrocki 1995; Podstawczyńska 2007). In the winter, this drop increases on average to about 10-15% (even by more than 40% on individual days), and in summer they are in the order of 2-6%. Direct radiation is suppressed even more than global radiation, while diffused radiation is stronger in urban areas than in rural areas (Olecki 1973; Hess et al. 1980). It should be emphasised, however, that due to radiation absorption's dependence on air pollution, actions taken in recent years to improve urban air quality have reduced the urban effect on solar conditions.

A city's ability to absorb solar energy is determined by surface albedo. The literature contains many results of albedo measurements in selected urban areas (sheeting, roofing felt, asphalt, brick, concrete, etc.), but far fewer works cite the results of averaged measurements for an entire part of a city. Obtaining such data requires the sensor to be placed high above buildings. Average albedo is influenced not only by the albedo of individual surfaces, but also by the city's geometry, which increases absorption through multiple reflections – the geometric factor alone can decrease albedo by several tens of percent points (Fortuniak 2008; Pawlak 2009). Therefore, for urban areas, albedo is relatively small – averaging 0.14 (Oke et al. 2017). Several years of measurements in Łódź indicate that values in city centre districts are lower, in the order of 0.07-0.09 (Pawlak 2009; Fortuniak 2010). The given values refer to snowless conditions, since snow cover increases albedo. However, due to the occurrence within the city of vertical surfaces not covered with snow, albedo in urban areas remains relatively low.

Relatively few measurement data relate to studies on the urban impact on long-wave radiation. Oke et al. (2017) suggest that incoming long-wave radiation is about 5-10% (20 Wm^{-2}) higher in urban areas than in surrounding areas. Preliminary results of research in Łódź suggest similar values (Fortuniak et al. 2015).

The remaining components of the heat balance of cities, in particular turbulent fluxes of sensible and latent heat, have been measured on a larger scale practically only in Łódź. They show the characteristic higher sensible heat flux than latent heat flux (Bowen coefficient at noon in the order of 1.5-2), the presence of a significant sensible heat flux after sunset and virtually constant (including at night) positive (directed from the surface to the atmosphere) latent heat flux (Offerle et al. 2006a, b; Fortuniak 2010). At the same time, the number of night-time cases of negative sensible heat flux (turbulent heat transport from the atmosphere to the urban surface) is relatively high compared to other cities.

Summary

Polish climatologists' achievements in urban climate research contribute significantly to the understanding of anthropogenic modifications to local climate. Their findings are consistent with results from other mid-latitude cities; they show the general patterns in Polish conditions and contribute to the development of this sub-discipline. Many of the urban effects depicted, such as the urban heat island, have already been relatively well recognised. Others, such as issues related to full thermal balance, including long-wave radiation and turbulent fluxes, require further study. New measuring techniques are providing great opportunities for urban climatology to develop. The widespread automation of measurement provides data from multiple locations at unprecedented temporal resolution, and remote-sensing techniques are increasing spatial resolution. The availability of relatively cheap sensors and direct data transfer capabilities have helped the measurement networks of not only scientific and research institutes to grow, but also those of government and local government institutions and commercial companies. These networks provide a significant amount of data, often in a very attractive form. Unfortunately, a frequent drawback of data from such sources is their questionable quality, not necessarily due to the quality of the sensors themselves, but primarily due to the lack of expert knowledge when determining the location of measuring points at the design phase (e.g. sensors are located in places that prevent proper ventilation or are directly exposed to sunlight without radiation screens). A lack of expert knowledge can also be seen in many "expertise opinions" or projects in which specific urban effects are treated very one-sidedly, without a full analysis of their potentially positive and negative effects. The recommendations contained in such studies can lead to costly undertakings that bring little real benefit. Therefore, beside typically cognitive research, one of the main challenges of Polish urban climatology is to disseminate knowledge about the impact of built up areas on local climate conditions. This will allow it to be used correctly in activities aiming to improve urban residents' quality of life in the era of modern climate change.

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S u m m a r y

The study reviews urban climate research in Poland. It was pointed out that the first meteorological measurements in Polish territories come from major cities and Polish researchers, such as Magier or Jastrzębowski, were aware of the impact of urban development on the local climate already at the early 19th century. The post-war achievements and trends in research on urban climate in major agglomerations like Warsaw, Cracow, Łódź, Wrocław, Lublin, Toruń, Poznań and the Tri-City are discussed in more details. It has been shown that the main urban effects, such as the urban heat island, have been studied in all these cities. At the same time, a specialization of individual research groups can be noticed. Next, the main findings regarding the city's influence on the basic meteorological parameters, such as temperature (urban heat island), air humidity, atmospheric precipitation and cloudiness, anemometric conditions, solar conditions or energy balance were referred. Review of these findings allows to conclude that the results for Polish cities coincide with the results for other cities located in similar climatic conditions. Polish studies do not only refine these regularities to national conditions, but also introduce new concepts to international literature. Final remarks emphasize the necessity to use the results more effectively in urban activities, in order to improve the living conditions in the cities and reduce the negative impact of cities on the environment.