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Interactions between thermal advection in frontal zones and the urban heat island of Wrocław, Poland

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With 10 Figures

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Summary

This paper deals with variability in the air temperature field of an urban area during thermal advection, associated with frontal zones, and its interaction with an urban heat island (UHI). Thermal changes experienced in Wrocław, Poland form the basis of this case study analysis. The discussion also contributes to questions concerning the definition of the UHI and ways to select UHI episodes from existing data sets. It is shown that changes in temperature generated during periods of advection are of short duration, only a few hours at most, but thermal contrasts between various parts of a city at such times are sometimes large, reaching an intensity of 5–6 K, even as large as 9 K. Thus, their intensity is comparable with that of the UHI occurring on cloudless and windless nights. The thermal influence of advection is often greater than that due to urban factors; it is only on occasions with less dynamic advection, that a concentric temperature field is formed due to the modified physical properties of the city. In the majority of cases, the thermal field is non-concentric and this is linked with the location of a frontal zone at any given time. The thermal effects of advection recorded in a data set might easily be viewed as episodes of UHI existence, especially if analysis is conducted based on the data derived from just two stations – one urban the other rural. On occasions when such 'quasi-UHI' occur the role of the location of the rural, reference station is also evaluated. Precise definition of the urban heat island can be of significance when conducting comparative studies of the UHI in cities located in different geographical zones and when making an urban climate synthesis.

1. Introduction

From the beginning of the 19^{th} century Earth's population has increased more than 5.5-fold, whereas the number of people living in cities has increased by more than 100 times. Now, more than half of the human population lives in cities and the rate of urban development continues to accelerate. The rapid progress in urbanisation and industrialisation has resulted in many environmental problems including alteration of the local climate. One of the most distinct, though unintended, climatic consequences of urbanisation is the modification of the air temperature field in cities, known as the urban heat island (UHI). It is probably not only the purest, but also the best-documented example of inadvertent climate modification. Studies of this phenomenon have been conducted for over 170 years (Howard, 1833; Landsberg, 1981; Oke, 1974, 1979, 1990) and it remains a research focus because of its practical significance to people living in cities.

Usually the urban heat island is defined as a positive thermal anomaly of a city if compared to the surrounding non-built-up area. The form and size of the UHI varies in time and space as a result of meteorological and urban characteristics.

The most distinct thermal effect in a city is to be expected at night during cloudless and windless weather conditions. This combination is conducive to the formation of considerable air temperature contrasts in urban areas that possess strongly differentiated urban environments. However, these factors are not the only ones leading to the modification of the air temperature field in urban areas. Previous research into the relations between thermal differentiation in the city and meteorological factors (in particular wind speed and cloudiness) showed that thermal differentiation, sometimes of substantial intensity, can occur in weather conditions generally considered as unfavourable to UHI development (Dubicka and Szymanowski, 2000, 2003). Further, examples of a positive thermal anomaly during the day and relative coolness of the city centre at night have been observed. The short-lived, often dynamic nature of such temperature field disturbances in the city suggested that the basic factor responsible for these changes are weather situations characterised by air mass advections. In these cases thermal effects caused by urbanisation (i.e. UHI in its standard meaning) are very often overcome by mesoscale variability in the air temperature field due to thermal advection. In the initial part of the paper the term: urban heat island (UHI) is understood to be a positive thermal anomaly of the city in comparison to the rural area ($dT_{U-R} > 0$ K), even if it is based on observations at only two stations (one urban, U and one rural, R), and irrespective of the processes leading to this anomaly.

The modification of the temperature field in urban areas resulting from changing synoptic conditions has been discussed in only a few studies. Wawer (1997) states that over 14% of the cases of UHI occurrence in Warsaw, with the intensity exceeding 3 K, are observed on days when frontal systems pass through. The role of warm and cold advection in deforming the temperature field in Łódź, Poland has been discussed by Kłysik and Fortuniak (1999). They describe the effect of warm air mass advection at night as being conductive to the formation of favourable thermal conditions in rural areas leading to an urban cool island, or negative heat island. Equally, cold advection at night is considered conducive to UHI intensification due to the cooling impact of incoming fresh air masses, mainly in the rural areas. Changes in temperature patterns under the influence of a cold front and precipitation in Mexico City are described by Jauregui (1997). He recorded the most intense heat island (8.7 K) when a cold front passed, rather than during nocturnal cooling in windless and cloud-free weather.

The main objective of the present study is to demonstrate the character of short-lived, mesoscale air temperature variability in the Wrocław area, that is mainly connected with thermal advection in frontal zones on one hand and the urban-generated heat island on the other. This leads to discussion of the definition of the urban heat island and ways to identify true UHI episodes. Further, it deals with ways to organise measurement systems and to locate meteorological stations in relation to the prevailing direction of advection. The analysis concentrates on the cases selected on the basis of the synoptic situation and the character of changes in weather conditions most connected with rapid changes in temperature fields.

2. Study area

Wrocław is located in the south-western part of Poland (51° N, 17° E) at about 120 m a.s.l. The altitude varies in the city area from 105 to 148 m a.s.l. The settlement is situated along the Odra River, however, there are no large water reservoirs nearby. Such environmental conditions make Wrocław a convenient urban location to study a relatively undisturbed urban climate and to verify urban climate models. The city has a population of about 640,000 living in an area of 293 km^2. 31.4% of the area is built-up and consists of housing estates, industry and warehousing, areas of service and administrative functions. Several different built-up types are present including a densely built-up centre with old 5-storey buildings, housing estates of tall (up to 11-storys) concrete buildings and residential areas in the outskirts. The rest of the city consists of green areas (36.6%), agriculture areas (28.9%) and water (3.1%) (Fig. 1). Wrocław is located in a mid-latitude climate zone characterised by a high frequency of polar air masses and a dominating western flow. Atmospheric fronts can be observed over

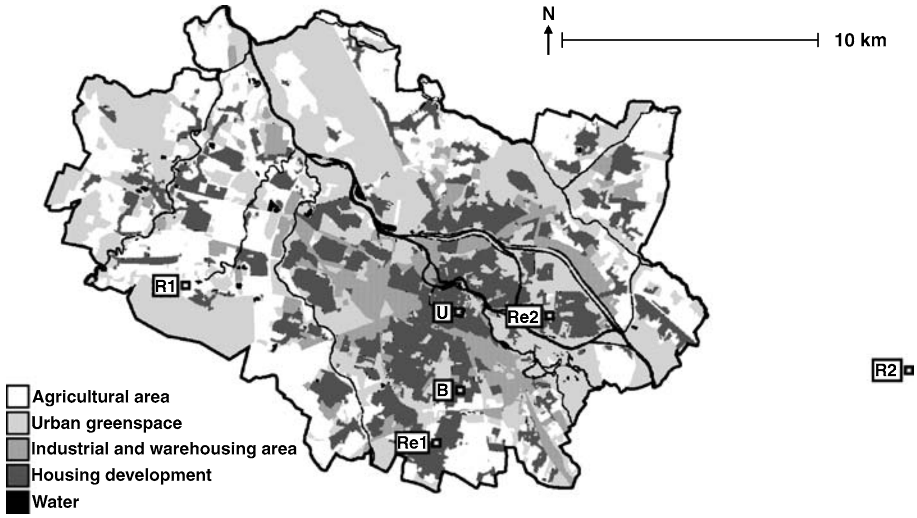

Fig. 1. Location of the automatic weather stations used in the study of the climate of the city of Wrocław

Poland on almost 230 days per year (Woś, 1999).

3. Data and methods

Research into the climate of Wrocław has been conducted since 1997 based on the measurement of meteorological elements by automatic weather stations. In the years 1997–2000 five stations located in different areas of development and land use type (Fig. 1, Table 1) collected data at hourly intervals. Each automatic station (Campbell Scientific Inc.) consists of a datalogger (CR10X), a temperature and relative humidity probe (Rotronic MP100A), a pyranometer (Skye Instruments SP1110), a net radiometer (Skye Instruments Q-7) and an anemometer (Young 05103 Wind Monitor). The air temperature and humidity sensors were mounted at 2 m a.g.l., and the anemometer at 3 m a.g.l. with the exception of the Re2 station, where the anemometer was mounted at 17 m a.g.l. Each station was located in a distinct land use type and mounted over grassy surface. Since 1997 there have been sporadic mobile measurements using two mobile meteorological stations equipped with psychrometers for air temperature and humidity measurements. These systems were deployed to fully evaluate the spatial structure and intensity of the UHI in Wrocław (Szymanowski, 2003a, b, c). Complementary hourly cloudiness and wind speed data were archived by the Airport Meteorological Bureau, Institute of Meteorology and Water Management in Wrocław, located 1 km south-east far from R1 station. Additional information on the

Table 1. System of automatic weather stations in the city of Wrocław climate researches

Station	Land-use type	Distance [km]/direction from city centre	Height [m a.s.l.]	Time resolution	Period
U	densely built-up area, up to 5 storeys	–	115	every hour every minute	Apr 1997–Mar 2000 Apr 2001–Mar 2002
B	housing estates, 5–11 storeys	3.5/S	129	every hour every minute	Apr 1997–Mar 2000 Apr 2001–Mar 2002
Re1	residential, dispersed development, up to 3 storeys	5.5/S	130	every hour	Apr 1997–Jun 1999
Re2	dispersed development, up to 3 storeys	4.0/E	116	every minute	Sep 1997–Mar 2002
R1	rural area	12.0/W	121	every hour every minute	Apr 1997–Mar 2000 Apr 2001–Mar 2002
R2	rural area	18.0/E	122	every minute	Apr 2001–Mar 2002

urban boundary layer (UBL) thermal structure was provided by acoustic soundings conducted using a monostatic, Doppler sodar located at the Re2 station.

To collect evidence of disturbed temperature fields some changes in measurement organisation were introduced to accommodate the dynamic character of these features. It is estimated that a warm front passes at 7–8 $m\,s^{-1}$, whereas a cold one traverses at 11–14 $m\,s^{-1}$. This means that the passage of an atmospheric front over the territory of Wrocław does not last more than 1–1.5 hour. Therefore the normal hourly frequency of measurement seemed inadequate. Teletransmission of measured data from loggers installed at automatic stations to a computer managing the network, based on a Global System for Mobile Communication links, made it possible to increase the measurement frequency to 1 per minute (Table 1). A computer, which initiates data transmission from each station every night (to reduce transmission costs), controlled the system. During each connection the datalogger time was synchronised with a time server.

In addition, meteorological stations were relocated after the 1997–2000 programme. Station Re1 was moved to the rural area about 10 km east from the city boundaries (R2) (Fig. 1, Table 1). This gave a system of four stations oriented in an west–east profile (R1–U–Re2–R2) compatible with the most prevalent direction of advection and completed with station B. The span of the profile (the distance between stations R1 and R2) was about 30 km. Measurements at the 1-min frequency were carried out in the period April 2001–March 2002. The case analysis comprises mainly the course of the air temperature and air temperature differences together with the wind speed and a direction at selected points. The lack of continuous recording of atmospheric precipitation (excluding station Re2) made it impossible to evaluate correctly its role in producing thermal differentiation. It is difficult to separate the advection effect from the cooling effect of water evaporation due to precipitation, particularly in the case of an atmospheric front with which precipitation is associated.

4. Basic characteristics of the UHI in Wrocław

The average annual intensity of the heat island in the centre of Wrocław, calculated as the difference in air temperature between the stations U and R1 (dT_{U-R1}) and based on hourly data from the period April 1997–March 2000, reaches 1.0 K (Table 2). It is only slightly lower than the average intensity defined by Kratzer (1956) for cities with a similar population (1.1 to 1.2 K). The thermal excess is greatest in the densely-built up central part of the city, and is lower in large housing estates of tall concrete buildings (0.7 K) and in residential areas of low estate houses (0.3 K in Re1 and 0.5 K in Re2) (Table 2). All variables are statistically significant at the level $\alpha = 0.05$ (Table 2). At night, the UHI intensity in compact settlements and housing estates with tall buildings is 2 or 3 times higher than the average values for the daytime. During the daytime dT_{U-R} does not exceed 0.5 K, irrespective of the type of settlement (Table 2).

In the period April 1997–March 2000 the maximal value of dT_{U-R} in Wrocław amounted to 9 K (Table 2), which was higher by 1.4 K than the maximum UHI intensity calculated using Oke's (1973) formula for European cities with a population comparable to that of Wrocław. If the UHI intensity is gathered using mobile measurements, it turns out that in favourable weather conditions the heat excess of the city can be higher than 10 K (Szymanowski, 2003a, c). The maximum UHI intensity of 9–10 K seems typical for cities with a population of several hundred thousand or even several million. In Poland the lower values have been recorded in Kraków (population 745 K) (7 K – Lewińska et al., 1982) and higher in Warsaw (population 1.635 M) (10.8 K – Wawer, 1997), as well as in Łódź (population 823 K) (12 K – Kłysik, 1998). A UHI intensity similar to that of Wrocław has been observed in Chicago (population of 6.1 M) (9.3 K – Ackerman, 1985), which is a much bigger city than Wrocław, but also in significantly smaller towns, such as Oulu (>9 K – Hara et al., 1999) – having the population of 100 K or Chapel Hill-Carrboro (8.9 K – Kopec, 1970) – with only 25 K inhabitants. Some of these results may, however, include advective effects which may explain why their values lie above Oke's relation.

In Wrocław UHI reach an intensity of 8–9 K occurs only at night. During the daytime the maximum UHI intensity is 5–6 K. The minimum values of dT_{U-R}, amounting to -6 K, may occur either during the daytime or at night. Cases when the city is cooler than the areas outside it can be

Table 2. Basic statistics and frequency of urban-rural air temperature differences (dT_{U-R}) in a different development. Wrocław, April 1997–March 2000

dT_{U-R}	Night				Day				Day and Night			
	U–R1	B–R1	Re1–R1	Re2–R1	U–R1	B–R1	Re1–R1	Re2–R1	U–R1	B–R1	Re1–R1	Re2–R1
Avg	1.6	1.1	0.4	0.4	0.5	0.3	0.2	0.5	1.0	0.7	0.3	0.5
Max	8.4	9.0	6.2	5.6	6.4	6.5	6.4	5.8	8.4	9.0	6.4	5.8
Min	−3.9	−3.8	−4.8	−6.1	−3.7	−4.9	−4.4	−4.0	−3.9	−4.9	−4.8	−6.1
Std	1.47	1.37	0.92	1.05	0.87	0.83	0.65	0.79	1.30	1.20	0.79	0.94
t-test ($\alpha = 0.05$)												
df	9514	9037	6993	6480	10624	10378	8002	5986	20139	19416	14995	12466
T	104.1	78.6	33.0	33.0	63.3	34.0	26.7	47.4	111.8	78.9	42.2	54.6
Frequency [%]												
< 0.0 K	3.8	10.8	26.5	22.9	19.1	29.7	31.6	18.2	11.9	20.9	29.2	20.6
> 0.5 K	77.1	60.3	31.9	50.5	42.8	27.6	23.0	47.0	59.0	42.8	27.1	48.9
> 1.0 K	50.6	38.6	18.0	21.2	17.3	11.2	7.9	17.2	33.1	24.0	12.6	19.3
> 3.0 K	15.5	9.9	1.1	0.8	2.0	1.1	0.2	0.6	8.4	5.2	0.6	0.7
> 5.0 K	3.8	1.7	0.1	0.1	0.3	0.1	0.0	0.1	2.0	0.9	0.0	0.1

observed in about 12% of the hours in a year (Table 2). An urban heat island is a typical phenomenon in Wrocław. Positive values of dT_{U-R} in the city centre are observed during more than 96% of hours at night and more than 80% in the daytime. Large intensity UHI (>5 K) are evident during 3.8% of night hours but on very few occasions during the daytime (Table 2).

The annual cycle of UHI intensity is strictly connected with meteorological conditions and the emission of artificial heat. The degree of interaction between these factors during the year sets the course of the UHI intensity. In the centre of Wrocław the highest average UHI intensity values are observed in the warm season, mainly in spring (May, April) (Fig. 2). The smallest intensity value is found in autumn (October). In the winter months, despite the increase in average cloud cover and wind speed, there is an increase in the UHI intensity. This is thought to be connected to the greater emission of artificial heat during the heating season.

The following meteorological factors exert the strongest influence on the UHI phenomenon:

- Wind speed – through turbulence which has a direct impact on energy exchange both in urban and non-urban areas,
- Cloudiness, which modifies the radiation exchange.

An increase of wind speed to over $4\,m\,s^{-1}$ at night, and over $1\,m\,s^{-1}$ during the daytime, irrespective of cloudiness, totally eliminates the UHI or causes a considerable reduction in its intensity (<1 K). The impact of cloudiness is practically

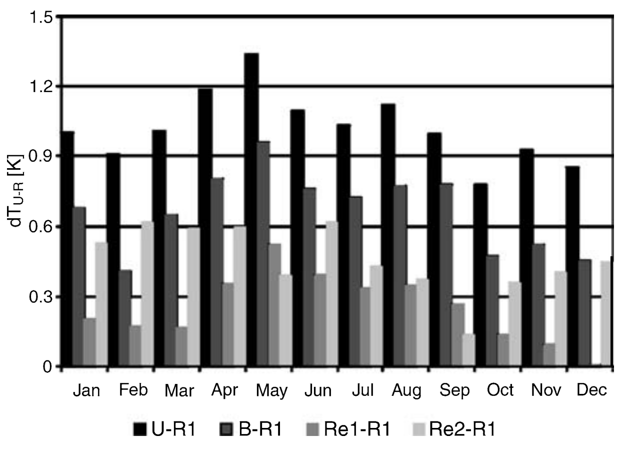

Fig. 2. Mean annual course of urban-rural air temperature differences (dT_{U-R}) [K] for Wrocław, April 1997–March 2000

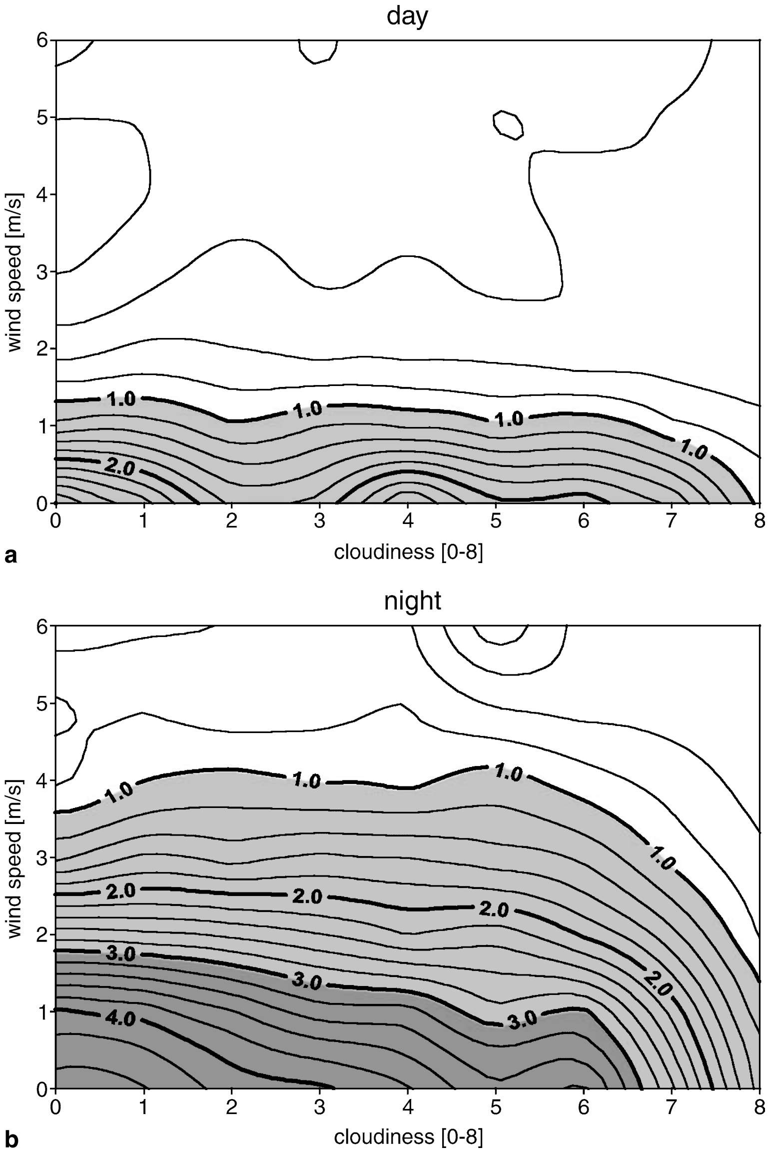

Fig. 3. Mean urban-rural air temperature difference (dT_{U-R1}) [K] depending on cloudiness [oktas] and wind speed [$m\,s^{-1}$] for Wrocław, April 1997–March 2000. **a** night time, **b** day time

unnoticeable during the daytime. At night only an increase in cloudiness to greater than 6 oktas is seen to diminish the UHI intensity (Fig. 3). It should be stressed that both wind and cloud cover have different impacts on the UHI, depending on the season of the year. Their strongest influence is observed in summer, and the weakest in winter. Wind speed is a more powerful factor limiting the UHI intensity (Table 3). Nevertheless it has been observed that in situations characterised by high wind speed and a total cloud cover, intense heat islands have been observed

Table 3. Correlation coefficients between urban-rural air temperature differences (dT_{U-R1}) and cloudiness and wind speed. Wrocław, April 1997–March 2000

Meteorological element	Day					Night				
	Spring	Summer	Autumn	Winter	Year	Spring	Summer	Autumn	Winter	Year
Cloudiness	−0.12	−0.04	−0.02*	−0.04	−0.06	−0.52	−0.59	−0.51	−0.41	−0.52
Wind speed	−0.22	−0.21	−0.25	−0.28	−0.21	−0.56	−0.61	−0.56	−0.53	−0.56

* Statistically insignificant at the level $\alpha = 0.05$

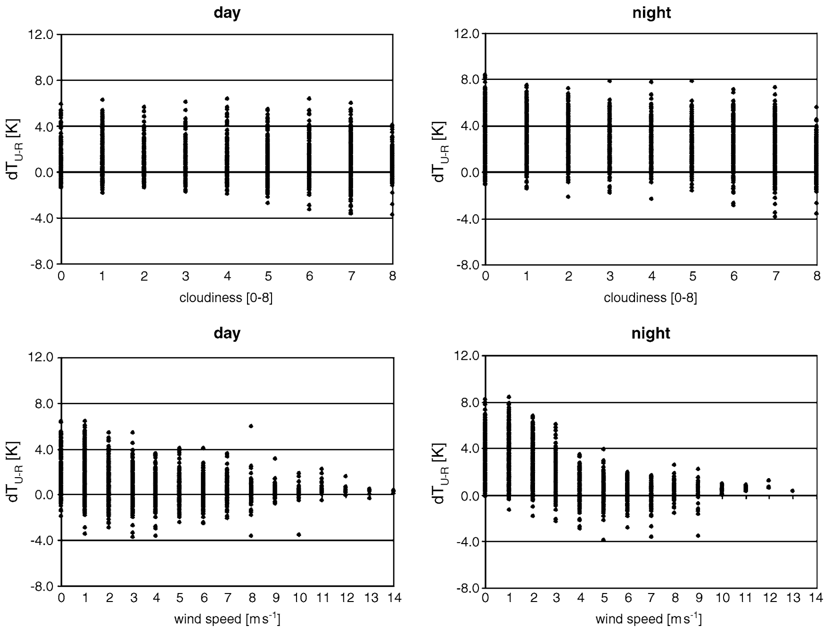

Fig. 4. Instantaneous urban-rural air temperature difference (dT_{U-R1}) [K] depending on cloudiness [oktas] and wind speed [$m\,s^{-1}$] for Wrocław, April 1997–March 2000

(Fig. 4). This is the impulse for the analysis in the present paper.

5. Results

The thermal effects of cold front passage are distinct if the process takes place during the daytime and, particularly in the summer near noon. Such a situation was observed on 16 July 2001, when a cold front over Poland was followed by a fresh polar maritime air mass that replaced the previous tropical air mass. The thermal impact on Wrocław area was observed at about 11:00 CET (Central European Time), when the air temperature nearly reached 27 °C. The frontal passage manifested itself as an increase in wind speed at station R1 from 1–2 $m\,s^{-1}$ to about 6 $m\,s^{-1}$, a change of wind direction and a rapid decrease in temperature by 7–8 K in 1–1.5 h (Fig. 5a, b). The decrease in air temperature was observed initially at station R1, after about half an hour in the city centre (U and B stations), and then in the eastern part (Re2), and finally on the leeward side of the city (R2) (Fig. 5b). As a consequence an UHI with the intensity of nearly 6 K that lasted about 2 h, was observed in different parts of the city (Fig. 5c). Obviously, the 'heat island' in this case is only a conventional notion, with the temperature recorded in built-up areas being referenced with respect to that at rural station R1. However, if instead we accepted R2 as the reference station, it would result, in the same period, in the occurrence of a UCI of a similar durability, but lower intensity (Fig. 5c). In addition, the advection cooling effect could in this case be intensified by a precipitation effect. Intense showers from Cumulonimbus clouds accompanying the front passage were recorded at station Re2 amounting to 17.7 mm during 1-hour episode. Unfortunately the lack of a recording of precipitation at the other stations made it impossible to evaluate correctly its influence on the air temperature field. After passage of the front the temperature field in Wrocław evened out within the next 2–3 h.

The effects of cold front passage were also observed on 27 February, 2002 in the late morning (Fig. 6). In this case a rapid decrease in temperature of 6–7 K was noted to be the result of the advection of a fresh cool polar air mass connected with the westerly cyclonic circulation. The frontal system passage brought about a change in wind direction from SW to W and an increase in speed amounting to 15 $m\,s^{-1}$ in gusts (Fig. 6a). A very rapid decrease in temperature led to the formation of an UHI with an intensity of 5 K (using station R1 as the reference) which lasted merely 40 min. In the same period, an UCI of similar duration and intensity with reference to station R2, was observed (Fig. 6c). In comparison with the case of 16 July, 2001 the front moved faster and therefore the temperature changes occurred over shorter periods.

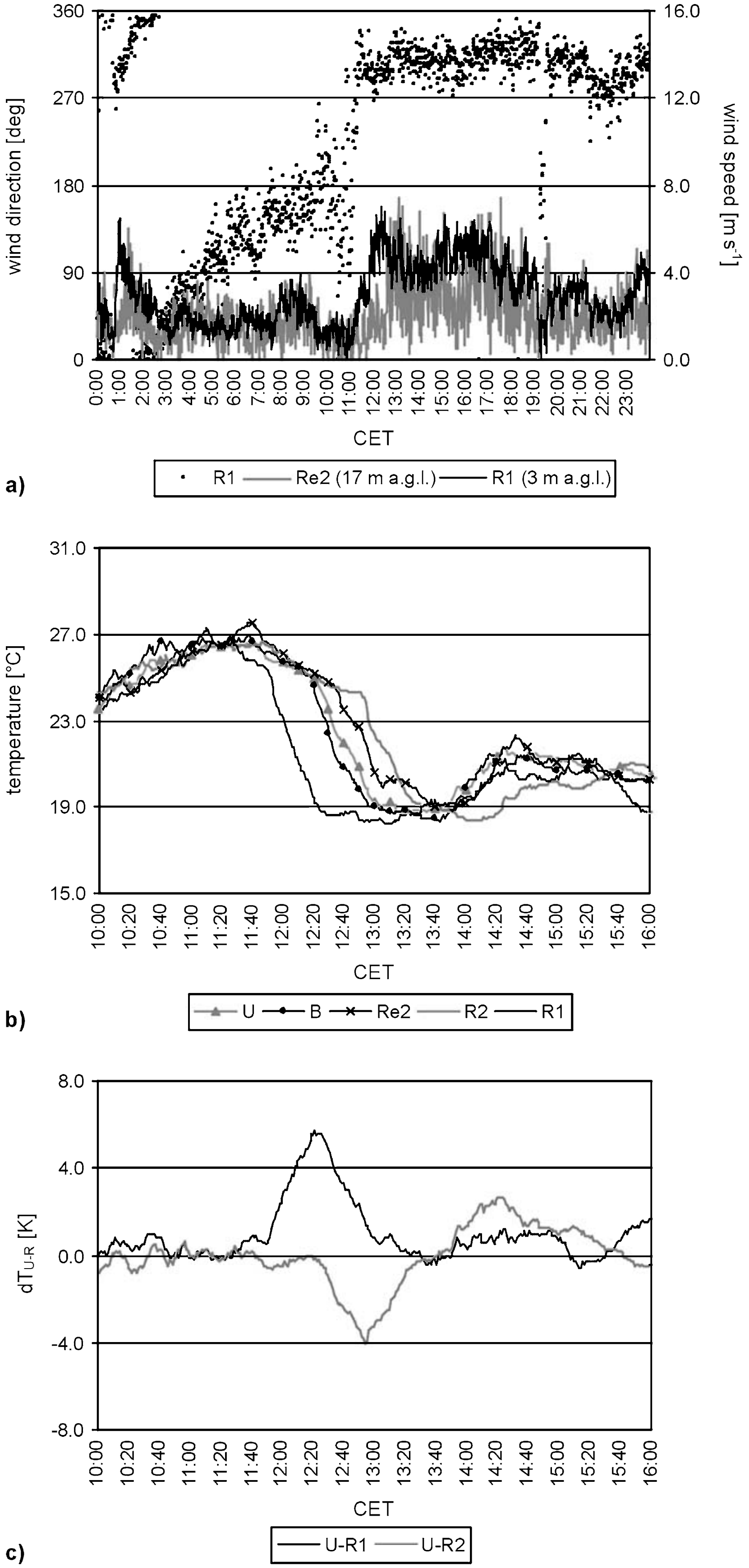

Fig. 5. Course of (**a**) wind speed [$m\,s^{-1}$] and wind direction [deg], (**b**) air temperature [°C] and (**c**) air temperature differences [K] in Wrocław, 16 July 2001

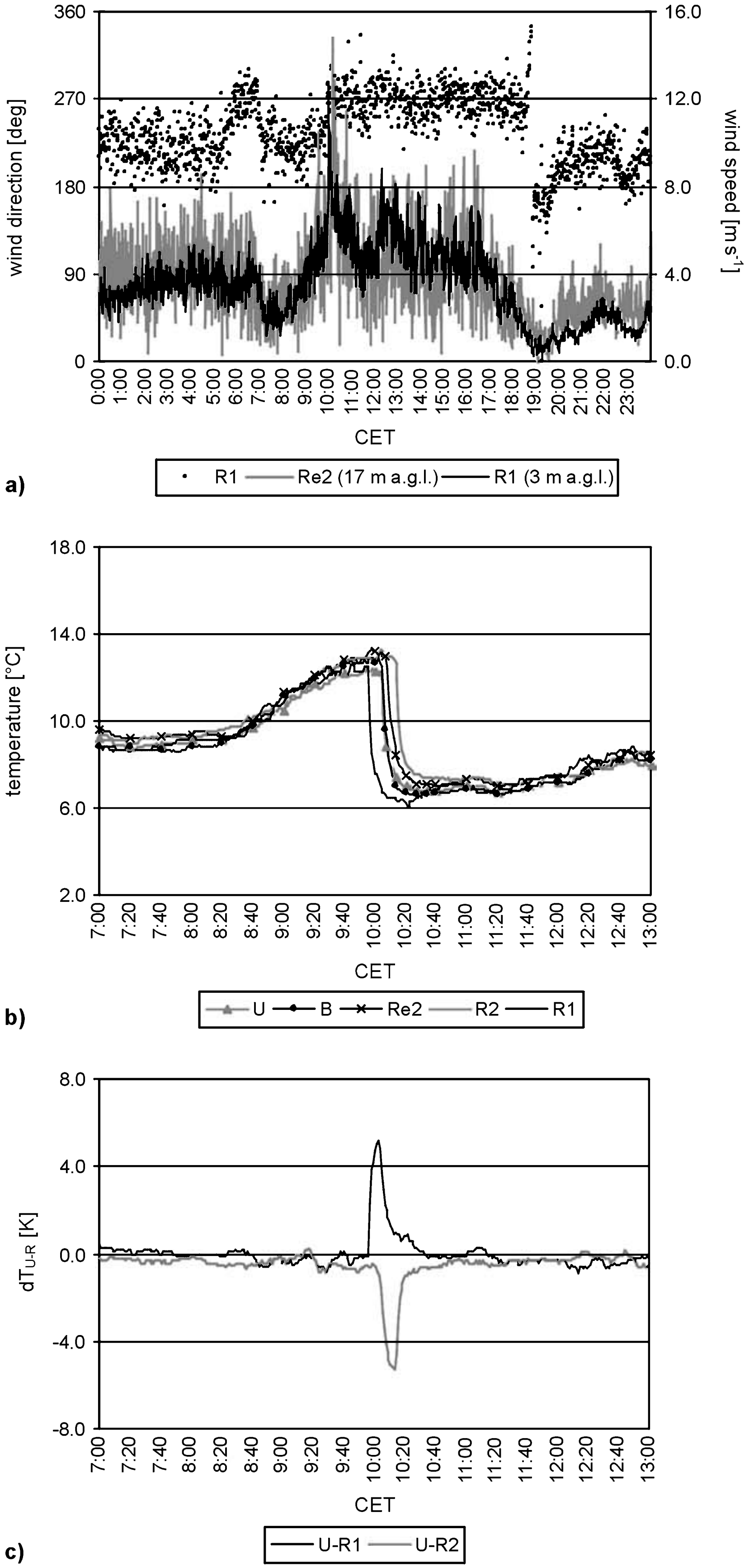

Fig. 6. Course of (**a**) wind speed [$m\,s^{-1}$] and wind direction [deg], (**b**) air temperature [°C] and (**c**) air temperature differences [K] in Wrocław, 27 February 2002

An essential aspect of cool advection concerns the states of the short-lived favourable (or unfavourable) thermal conditions in the city. Whether a heat island or a cool lake is observed depends on the way the UHI mathematical formula, defined as the difference in temperature at the urban station and the rural station (dT_{U-R}), is applied as well as the location of the rural reference station in relation to the direction of the oncoming front. Actually, in such cases the thermal differentiation in the city area is characterised by a configuration that is not concentric and only to a very slight extent depends on the thermal inertia bestowed by the physical properties of the built-up area. On the other hand, in some cold advection cases we have analyzed, despite their dynamic nature, the impact of the urban fabric parameters is strongly marked so that they distinctly influence the spatial air temperature field distribution in Wrocław. Such a situation was observed on 17 May, 2001 during the cold front passage connected with a low-pressure system with its centre over southern Scandinavia. The passage of the frontal system, which was followed by a fresh polar maritime air mass, was recorded in the afternoon (13:00–15:00 CET) in Wrocław. The consequence was a rapid decrease in air temperature, amounting to as much as 10 K at station R2 (Fig. 7b). Such a substantial decrease in temperature on the eastern side of the city and its dissimilarity in relation to the western side might be further complicated by the occurrence of occasional showers from Cumulonimbus clouds. This could be the reason why station R2 stayed so cold in comparison with station R1. An increase in wind speed of up to 8 $m\,s^{-1}$ in gusts was recorded only during the front passage, then it dropped to 2 $m\,s^{-1}$ (Fig. 7a). The thermal effect of this fresh air mass advection was observed initially at station R1, and after about 15 minutes – at station R2, 30 km away. Only after another 15-min, was the decrease in temperature within the city noted (U, B, Re2) (Fig. 7b). This example probably testifies to the role of the built-up area in modifying the temperature field. In this case the changed physical properties – increased admittance and roughness at lower wind speed (weaker turbulence) – are the direct reason for the city's inertia which maintained the energetic *status quo* for about half an hour after passage of the front. In addition, the decrease in temperature in the city took longer. As a result, the UHI which lasted about 2 hours (with reference to station R1) was created and it gradually turned into the nighttime UHI (with reference to station R2).

The cases of cold advection discussed above took place during the daytime. At night the course is actually similar to that during the daytime, unless a prior radiation-based heat island is observed. In such cases the short-lived temperature field modification effect can be as distinct as that during the daytime. An example of a nighttime cold front passage was observed on the night of 11/12 April, 2001. Before the front passed, with no cloud cover at lower altitude and very low wind speeds, a heat island with an intensity of 4 K was present in Wrocław area (Fig. 8a, c). The gradual increase in wind speed connected with the approaching front brought about an intensification of turbulence and, consequently, an increase in mixing in the atmospheric boundary layer leading to the destruction of the previously formed inversion layer and a relative increase in temperature (Fig. 8b, d). The effects of this were observed between 23:30 and 2:00 CET in the rural area (R1; unfortunately there are no measurements at station R2 on this occasion) and in the high-rise area (blocks of flats, B), and between 1:30 and 3:00 CET in the low-rise area (Re2). The relative increase in temperature connected with the mixing probably only manifested itself in those parts of the city where a ground inversion existed and not in areas with an elevated inversion occurrence, which are additionally characterised by increased roughness (U) (Fig. 8b). The effect of the temperature increase in the suburbs and the lack of a thermal response in the city centre caused a complete UHI reduction before the front approached. Only during its passage (3:30–4:30 CET), was there a short-lived (nearly 2 hours) differentiation of the temperature field, consistent with the previously discussed model. It amounted to 2 K in the city area (Fig. 8c).

The course of events leading to the reduction of the already formed heat islands demonstrated a considerable similarity to those during warm air mass advection, an example of which is the warm polar air mass advection experienced on the night of 10/11 October, 2001 (Fig. 9). In this case the destruction of the UHI, induced by an

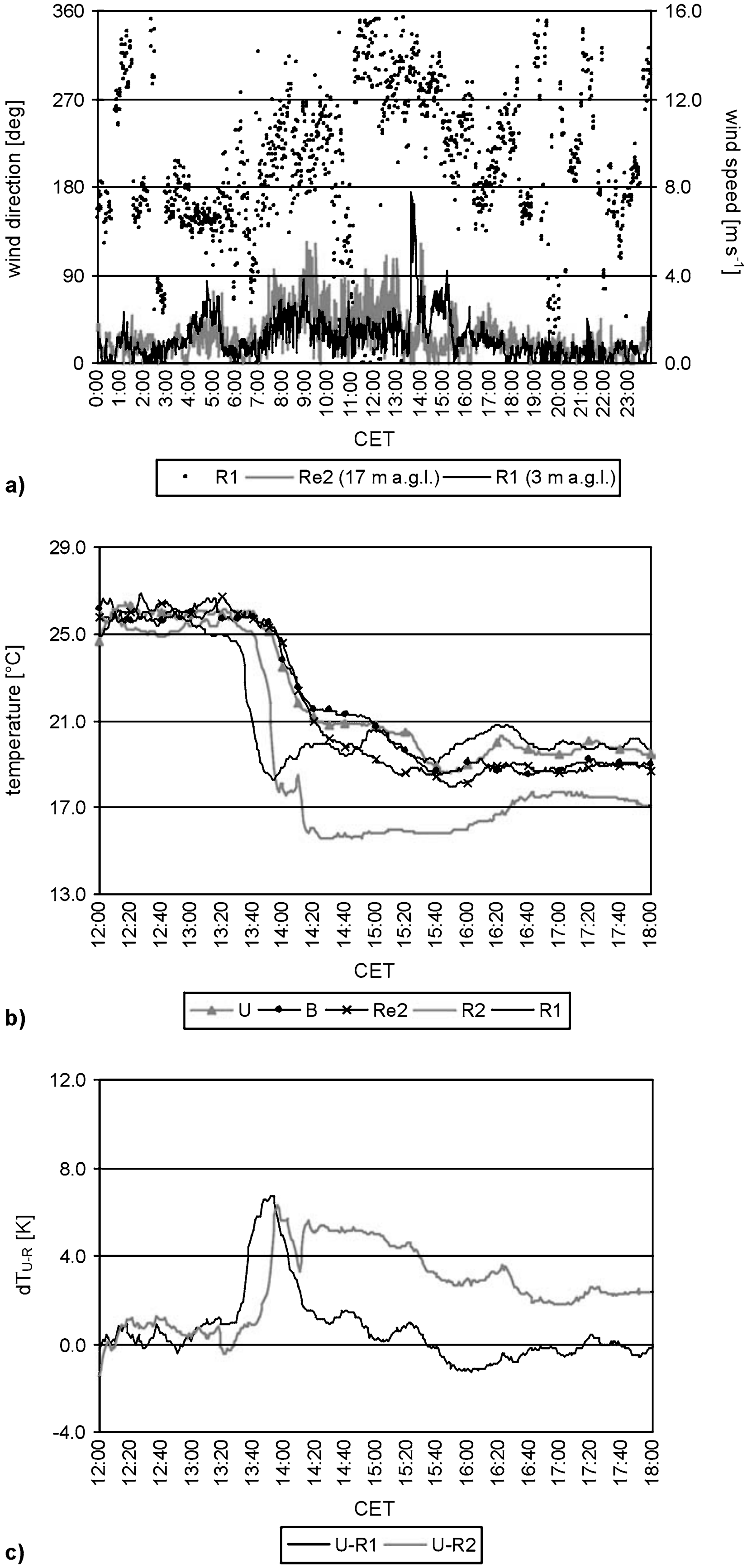

Fig. 7. Course of (**a**) wind speed [m s^{-1}] and wind direction [deg], (**b**) air temperature [°C] and (**c**) air temperature differences [K] in Wrocław, 17 May 2001

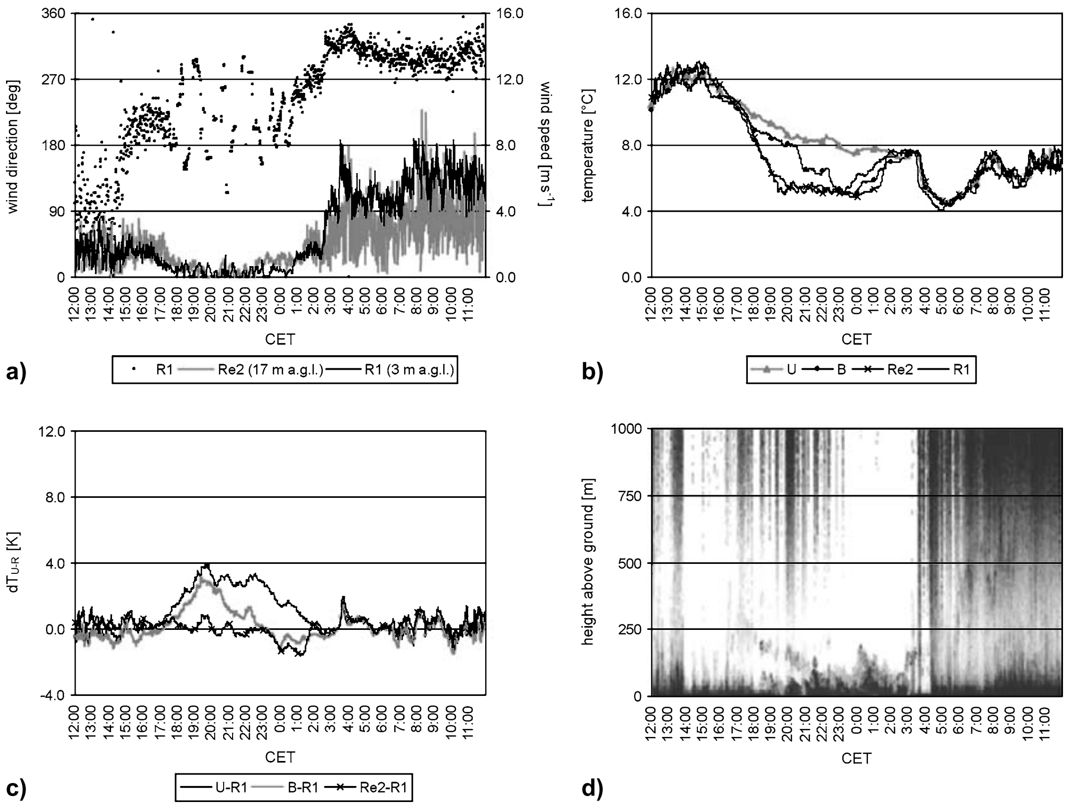

Fig. 8. Course of (**a**) wind speed [m s^{-1}] and wind direction [deg], (**b**) air temperature [°C], (**c**) air temperature differences [K] and (**d**) sodar echo in Wrocław, 11/12 April 2001

increase in temperature in the suburbs, was noted (R1, Re2). It was less distinct in the housing estate (B) and actually unnoticeable in the city centre (U) (Fig. 9b). But because the nature of warm front passage is less dynamic than that of a cold front, the moment the warm front passed is difficult to define explicitly. Hence, an increase in temperature leading to the reduction of the UHI could be caused to some degree by turbulence processes in the boundary layer, and to a greater extent by the thermal impact of the incoming air mass, less manifested in the areas where increased roughness and dense urban fabric hindered removal of the pre-existing air.

The processes resulting in heat advection and temperature field modification also include a complex foehn-derived phenomena due to air mass transfluence as it flows over the Sudety Mountains orographic barrier. One of the fundamental climatic consequences is adiabatic warming of air masses flowing down the lee side of a mountain massif (foehn wind) which causes considerable warming in the mountain forelands. The frequency of foehn winds and foehn-derived phenomena in the vicinity of Wrocław has been estimated at 70 days a year (Kwiatkowski, 1975). The most distinct weather consequences of foehn winds can be observed during low foehns, i.e. those reaching the ground in a given area. The effects of an upper foehn impact, i.e. a foehn stream passing over the stagnant pre-existing air layer, are less distinct, often only indirect. Apart from a signalled increase in temperature and wind speed, the general weather consequences of foehn winds means a decrease in relative humidity and cloudiness, as well as an increase in solar radiation; a characteristic symptom is the occurrence of Lenticularis clouds. The 'foehnized' air masses gradually transform due to the impact of ground and mixing with the original air mass and lose their foehn characteristics as distance from the mountain barrier increases. An formidable barrier that hinders the movement of foehn currents onto the far Sudety Mountain foreland is the Odra river valley, where the transformation is enhanced by saturation with water vapour and a change in the atmospheric stability (Kwiatkowski, 1975).

The impact of foehn-derived phenomena in modifiying the temperature field of Wrocław was

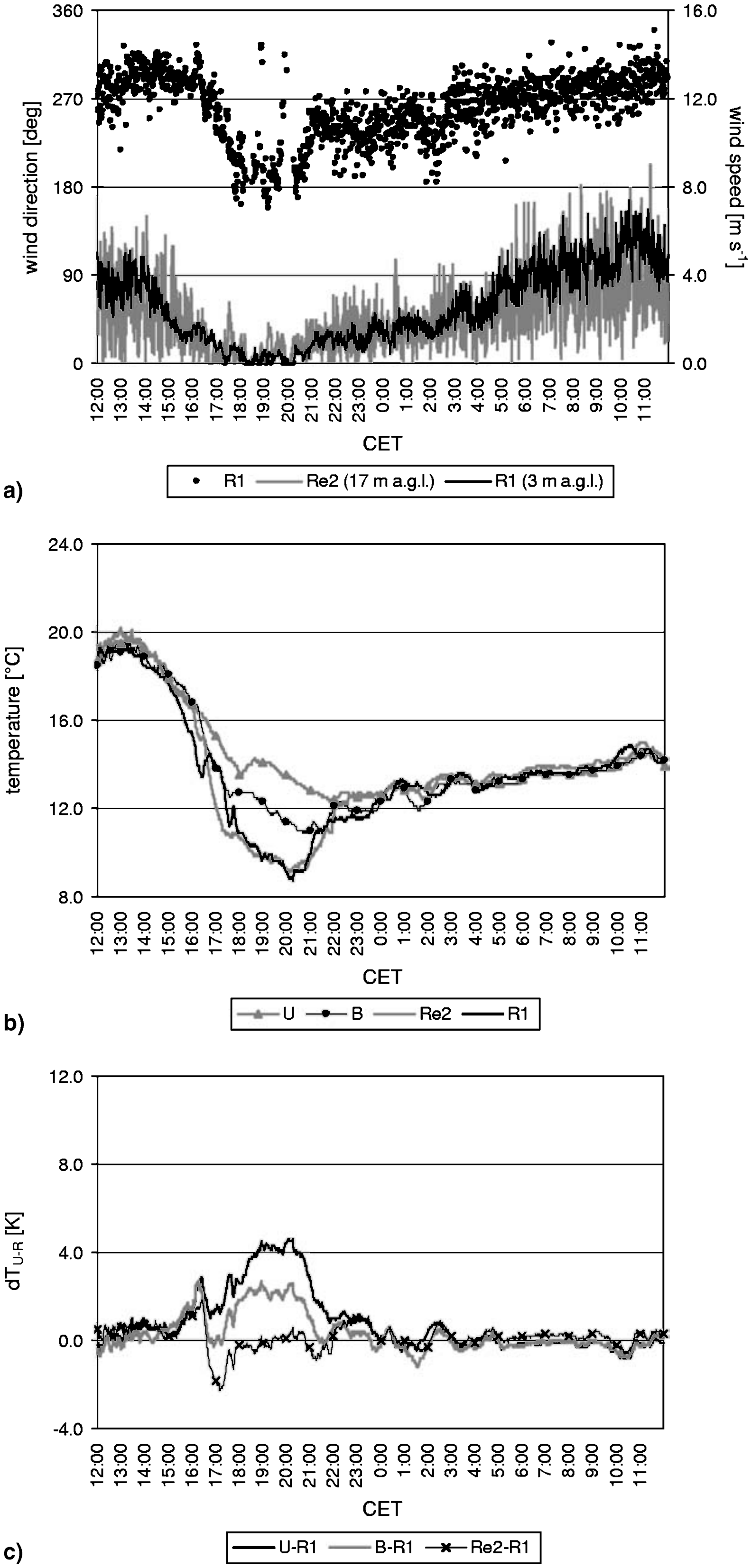

Fig. 9. Course of (**a**) wind speed [m s^{-1}] and wind direction [deg], (**b**) air temperature [°C] and (**c**) air temperature differences [K] in Wrocław, 10/11 October 2001

observed on the night of 2/3 February, 2002 during the transfluence of polar maritime mass over the Sudety Mountain barrier induced by southwesterly circulation in the high-pressure system. In the period preceding arrival of the foehn, i.e. in the afternoon and the evening of 2 February, a

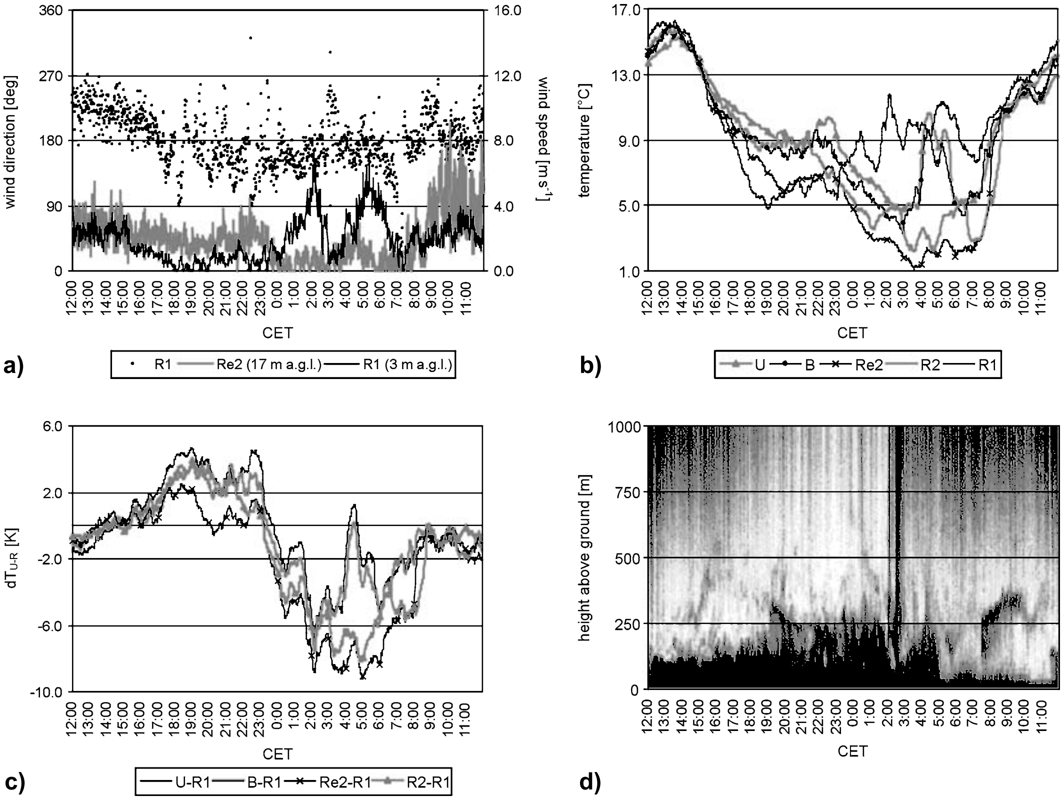

Fig. 10. Course of (**a**) wind speed [m s^{-1}] and wind direction [deg], (**b**) air temperature [°C], (**c**) air temperature differences [K] and (**d**) sodar echo in Wrocław, 2/3 February 2002

tendency for a UHI to form due to radiation cooling was observed. At about 19:00 CET the UHI intensity exceeded 4 K (Fig. 10c). At about the same time the first symptoms of the foehn wind impact were noted – an increase in temperature (Fig. 10b) and a decrease in relative air humidity in the vicinity of station R1. A systematic increase in temperature, though with some fluctuations, was observed at this station for the rest of the night. Its main phases were connected with the intensification of foehn activity expressed by an increase in wind speed, especially in the time span: 0:00–3:00 and 4:00–7:00 CET (Fig. 10a). The temperature increase recorded in the west part of the city was not evident either in the built-up areas, or on the east part of the city. The only strong foehn impact related to an increase in wind speed and rapid temperature fluctuations recorded in the built-up areas (U and B stations) between 4:00 and 6:00 CET. At the same time an insignificant thermal reaction (1–2 K) was observed at stations Re2 and R2. In this region, i.e. in the east part of the city, the foehn wind had the characteristics of an upper wind flowing over the old air mass. A sodar echo recorded at station Re2 confirms the occurrence of a strong ground-based inversion, 200–250 m high at that time, above which there were structures characteristic of air-flow processes (Fig. 10d). A confirmation of this interpretation is the low wind speed at stations Re2 and R2. It is noteworthy that these stations are located in the neighbourhood and north of the Odra river valley, as opposed to station R1 which is located much further south of the valley (Fig. 1). The flow of the foehn stream over the strong ground inversion could then be enhanced by the effect of the "conserving" Odra valley impact.

In summary, it can be stated that in this case the foehn thermal effect was observed mainly in areas to the west of the city. In the built-up areas it was evident only during the short-lived impulse of strong wind that was able to disturb the thermal structure of the pre-existing air mass within the densely developed urban area. On the east side of the city the factor limiting the impact of the foehn was a strongly formed ground inversion which was caused by air stagnation connected with the concave form of the Odra valley. As a result, the thermal differentiation of the city area, amounting to 9 K (Fig. 10c), was evident, but its thermal structure was non-concentric, the warmest zone was in the west and south-west of the city, cooler built-up areas and a cold, sub-inversion zone on the eastern side.

6. Discussion

Analysis of short-lived modifications of the temperature field in this city under the influence of advection and its interaction with urban properties, gives rise to the following basic questions:

1. Which instances of the variability in the thermal field of the city might be regarded as belonging to the phenomenon of the urban heat island, and, in consequence, what is the definition of the UHI?
2. How should one separate such episodes of urban heat island formation from existing data sets?

The answer to the above questions exceed the limits of the main goals set for the present paper; nevertheless, the conclusions reached and presented here might initiate a discussion about the definition of urban heat islands.

In climatological practise it has become customary to accept the occurrence of positive temperature differences between an urban and a rural station (dT_{U-R}) as an episode of the UHI (e.g. Parry, 1956; Pooler, 1963; Hage, 1972; Lee, 1979a, b; Unwin, 1980; Ackermann, 1985; Yagüe et al., 1991; Moreno-Garcia, 1994; Jauregui, 1997; Figuerola and Mazzeo, 1998; Kim and Baik, 2002). Simply accepting such a mathematical attitude, means that thermal effects caused by air mass advective events are included in the data and are viewed as episodes of the UHI. This is so even though thermal differentiation caused by the influx of the air mass is perhaps only complemented by the influence of urban factors in certain situations, while in the majority of cases it is connected only with the consequences of the location of stations in the area of the city and around it. In this case the importance of geographic placement of the reference station relative to other stations cannot be overestimated. If it is situated on the side of a city from which cold atmospheric fronts are more frequently dislocated, the UHI is likely to be formed with a higher frequency. In contrast its location on the opposite side of a city would have caused a more frequent appearance of the UCI, not UHI. It is to be understood that in such situations one can not talk about the UHI, or the UCI in a conventional way since the spatial structure of these phenomena is more linked with the location of a frontal zone at a given moment than any urban influence. The effects of such thermal features recorded in data sets might be, to a certain extent, minimized by referring the temperature derived from an urban station to the average temperature obtained from two or more stations located outside a city (dT_{U-Ravg}) (Matwiejew, 1979; Lewińska et al., 1982; Dubicka, 1994; Morris and Simmonds, 2000; Morris et al., 2001). It may be possible to do this in some cases, if so it is advisable that the role of advection be taken into consideration in the design of the measurement system from the start of the project.

Despite the fact that the thermal excess of cities has been observed and described from the first half of the 19^{th} century (Howard, 1833), it was not until the middle of the 20^{th} century (Duckworth and Sandberg, 1954; Manley, 1958) that the expression "urban heat island" was introduced to describe relative islands of higher temperature formed by cities in the "sea of coolness" of non-urbanised areas, has since become an integral part of climatological terminology. The extent to which this analogy was appropriate and well aimed has been proved by measurements carried out by means of mobile meteorological stations. If the change in air temperature from the areas surrounding the city to its centre is drawn, one obtains a geomorphic-like representation of an island that consists of cliff, plateau and peak (Oke, 1987). However, such a "semantic" attitude tends to limit UHI episodes to situations in which thermal differentiation in the city area is dominated by its fixed physical structure, or morphology, both in advective and non-advective cases. Such a method of selecting the UHI episodes is, in practice, difficult to apply since it requires a great number of data to be analysed, obtained mainly from stations outside the city, ideally in conjunction with detailed synoptic analyses. In practice the number of appropriate non-urban stations is often very limited.

In consequence, episodes of the UHI should be selected on the grounds of the influence of urban factors which through physical processes lead to the shaping of the thermal differentiation of built-up areas (Oke, 1982), especially in connection with definite weather conditions. In the context of such a ''physical'' approach one should pose the question: have all the processes conducive to the shaping of an urban heat island under the influence of the various components of land development been identified? The solution to this problem in the context of selecting UHI episodes seems to be the apparent consensus between the ''mathematical'' and the ''physical'' attitude, which requires advection situations be excluded from the whole data set. Theoretically, this should limit the occurrence of positive or negative thermal anomalies in a city to those shaped by the impact of urban and other anthropogenic factors. This method, however, entails significant practical difficulties – it requires the origin of each episode to be considered and analysed. For the case of sets characterised by a high frequency of measurements (e.g. every minute) this might be especially problematic because of the great number of data; similarly, it could be difficult in the case of sets with a low temporal resolution (e.g. 3–4 times per day) because of insufficient information to carry out a reliable analysis of an incident.

The limitations mentioned above hinder significantly the ability to accurately study the UHI, especially if one does not take into account advection episodes that, despite their short-lived nature, are quite prominent and can distort characteristics such as the intensity and frequency of the phenomenon. Within the limits of the present paper it is not possible to accurately list separate episodes of thermal differentiation in Wrocław – hence, it is hardly possible to estimate the impact that advection situations exert on the data set. A preliminary analysis of synoptic situations from the period of April 2001 till March 2002 shows that about 194 situations of frontal passage took place, out of which 106 were cold fronts, 61 were warm fronts, and 27 were occluded. Nevertheless, one has to bear in mind that only in some of the cases of thermal advection were substantial contrasts in air temperature observed within the city limits.

The problems considered here have special relevance to comparative studies and in the analysis of the data derived from different cities, particularly those situated in the zones with different atmospheric circulation characteristics. The only solution then seems to be the procedure applied when constructing models – a preliminary selection of the material, mainly by setting up a defined criterion, e.g. by limiting the data set to the situations characterised by constant weather conditions, most often of a radiation type. A drawback of such a ''model-based'' attitude is the fact that all the remaining cases, including the advection ones considered here, are excluded from analysis, which leads to the limitation of the set. The advantage of this approach, however, is the possibility of carrying out comparative studies of heat islands formed in cities characterised by diverse morphology, situated in different climate zones, or the possibility to compare changes in the course of temperature depending on the land-use or land development type (Fortuniak, 2003).

7. Conclusions

Summing up, one has to underline that large thermal contrasts appearing in a city are not always the result of the influence the city itself exerts on the local climate. Such a variation is often shaped by the impact of thermal advection while a frontal zone is passing. The location of meteorological stations in space, especially of a reference station in relation to the direction of advection, is of a significant importance in causing the occurrence of a quasi-UHI or -UCI effect. Studies where the data are collected automatically rather than being specifically selected for study at the start, are those where difficulties are most likely to arise. This is especially the case for cities characterised by a high frequency of advection events, ones when there are instances of thermal differentiation that are not the result of the influence of urban factors, yet still manifest intensities and patterns that give the appearance of a heat island. An additional problem case occurs when the influence of the city is diminished due to the domination of advection over processes conditioned by urban factors. During dynamic advections, accompanied by a high wind velocity, the speed at which the original air mass is removed from among the buildings is so high, that the impact of urban factors is practically absent. On the other hand, in some cases, especially when advection is less dynamic, the role of the changed physical characteristics of urban areas can still be discerned. In cities with a more compact settlement, including taller buildings, than those found in Wrocław and which are characterised by a stronger thermal inertia in the urban canopy layer, the impact of the physical characteristics of a city are still evident despite extremely dynamic advective influences.

Perturbations of the urban temperature field formed during atmospheric mass advection, despite their short-lived nature, suggest that one should look at the phenomenon of the UHI and methods to detect it in a new way. These concerns should be treated as another voice in discussion of the UHI and its nature. Problems connected with attempts to precisely define the urban heat island, while of relatively little importance in the case of single analytical studies, might cause difficulties when conducting comparative studies of the UHI formed in cities located in different geographical zones and when seeking urban climate syntheses.

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