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DIFFERENTIATION OF EQUIVALENT TEMPERATURE IN A TOWN (WITH CRACOW AND HOMBURG AS EXAMPLES)

Abstract: The equivalent temperature belongs to the oldest biometeorological indices. It is a significant measure in the studies on the local climate and bioclimate of towns. It is accepted as one of the indicators of the thermal stress to a human body. During 1997-1999 the field experiment of the equivalent temperature in Cracow (Poland) and Homburg (Germany) was carried out. It has been found that this index reflects well the differences between bioclimatic conditions of the downtown and non-urban area. The crucial role in the distribution of the equivalent temperature in Cracow and Homburg is played by the size of the town and a relief conditions in which both towns are located.

Key words: bioclimate, urban climate, bioclimatic index, equivalent temperature, Cracow, Homburg.

1. Introduction

Urban climate differs significantly from the climate of non-urban areas. According to Landsberg (1981) a town, when compared with a non-urban area, is characterised by a weakened incoming solar radiation, higher air temperature, higher precipitation, lower relative humidity, lower wind speed and a much higher air pollution. For human beings, a considerable modification of a bioclimate, which is determined based on the sensible temperatures, including the equivalent temperature as well, is of particular importance.

The equivalent temperature can serve to determine the degree of sultriness, and to calculate cooling power and the total heat content in the air. It is a biometeorological index, obtained from using appropriate empirical formulae. It combines air temperature and humidity, it informs us about the heat balance of a man and how a man senses the air as sultrily. The equivalent temperature also expresses the total heat content in the air which consists of the stream of the sensible and latent heat. The equivalent temperature is defined as the temperature which the air would have (at a constant pressure) if all water vapour in the air condensed and the evaporation heat released this way were completely used for heating dry air (Cena, Gregorczuk 1966). In a case where the air temperature is high (>17^{0}C) and so is the relative air humidity (>85%), the process of the heat release by a human body is hindered. This leads to the heat retention in the body and the sultriness feeling. At that moment numerous physiologic reactions are triggered in the human body, among others, accelerated blood circulation, increased pulse rate, intensified lung ventilation and perspiration. The equivalent temperature (Te) is accepted as one of the human body thermal stress indices and is calculated in the following manner:

$$Te = t + \frac{0{,}622 \cdot r' \cdot e}{p \cdot cp}$$

where:

Te in ^{0}C
t = air temperature in ^{0}C
r´ = evaporation heat of water in Jkg^{-1}
e = water vapour pressure in hPa
p = air pressure in hPa
cp = specific heat of air at constant pressure in $Jkg^{-1}K^{-1}$

It is accepted that Te > 56^{0}C defines the limit of sultriness (Flach 1981). A more detailed assessment of the thermal feeling differentiation can be performed using the Robitzsch and Leistner's physio-climato-graph (Flach 1957; Cena, Gregorczuk 1966).

Te (^{0}C)	**Thermal feeling**
< 18	chilly
18-24	cold
24-32	slightly cold
32-44	comfort
44-56	slightly sultrily
> 56	sultrily

The parameters necessary for calculating the equivalent temperature (air temperature, air pressure and water vapour pressure) belong to the standard measurements taken at meteorological stations. They might also be obtained by additional studies on local climate.

This work is based on the field studies performed by using a car equipped with instruments for measuring the air temperature, humidity, wind speed and direction. The measurements were taken in two towns: Cracow and Homburg. The air temperature and specific humidity were measured continuously at various measuring sites along a given route in the town. The measurements have not been taken simultaneously in all the sites, but with a certain delay. Therefore, they were converted to a standard measurement timing, i.e. to the start time for the measuring. The changes of particular measured elements served to correct the particular values in the measuring sites and, then, they formed the basis for calculating the equivalent temperature.

This paper presents the distribution of the equivalent temperature in two towns, differing significantly as to their sizes, number of inhabitants, type of built-up and orography. The detail studies on finding the regularities in the differentiation of the equivalent temperature were performed using extensive materials from Homburg, which represents a small town.

2. Location of Cracow and Homburg

Cracow is located at the junction of three large morphostructural units: the Cracow Upland, the Sandomierz Basin and the Carpathian Foothills, all of them lying evenly with parallels of latitude, in southern Poland. The relief of the city is very diversified, comprised of the Cracow Upland, the Carpathian Foothills (the elevations exceeding 500 m a.s.l.), the plains in the Vistula valley (ca. 200 m a.s.l.) and in the Krzeszowice Graben. As it is a large, urbanised area (ca. 750,000 inhabitants), the natural climatic conditions are strongly modified by the local factors which affect the area over a range of several tens of metres to several tens of kilometres. At present, Cracow represents an extensive urbanised complex with a belt pattern and a complicated spatial-functional structure. The historical urban complex of Cracow is surrounded by two parallel belts of built-up area which extend along the Vistula river southward and northward. The northern belt consisting of compact built-up complexes forms almost a continuous zone of urban investments and connects downtown of Cracow with the industrial complex of Nowa Huta. The southern belt comprises the most recent complexes with loose, multifamilial housing estates (Mydel 1994).

Homburg is located in the south-western part of the German Federal Republic, close to the French border in the Saar region. It is an undulated upland placed ca. 300 m a.s.l. The town of Homburg has 48,000 inhabitants and is located on the plain; only the hospital is located on a hill ca. 30-50 m above the town. The western slopes of the hills surrounding the town are forested, the remaining ones are under farming. In Homburg there are three large industrial centres: the modern chemical and electrical industry is located in the north-east and in the west, while the heavy industry is in the south. Downtown of Homburg has a compact, many-storied housing estates while family houses predominate in the remaining part of the town. The Erbach quarter with its many-storied built-up area is an exception here. The green areas are less extensive there than in other parts of the town.

3. Nocturnal distribution of the equivalent temperature

Based on the field measurements performed during 1997-1999, the model of the average differentiation in the equivalent temperature in a town (Kühne 1998) was developed for Homburg. The regularities found for the small town, have been then confirmed based on the field studies and meteorological analysis in Cracow.

Results of the measurements taken in Homburg at night of 11/12 August, 1997 (Fig. 1) are an example of the spatial distribution of the equivalent temperature. The area of the maximum equivalent temperature values comprises a southern section of the main

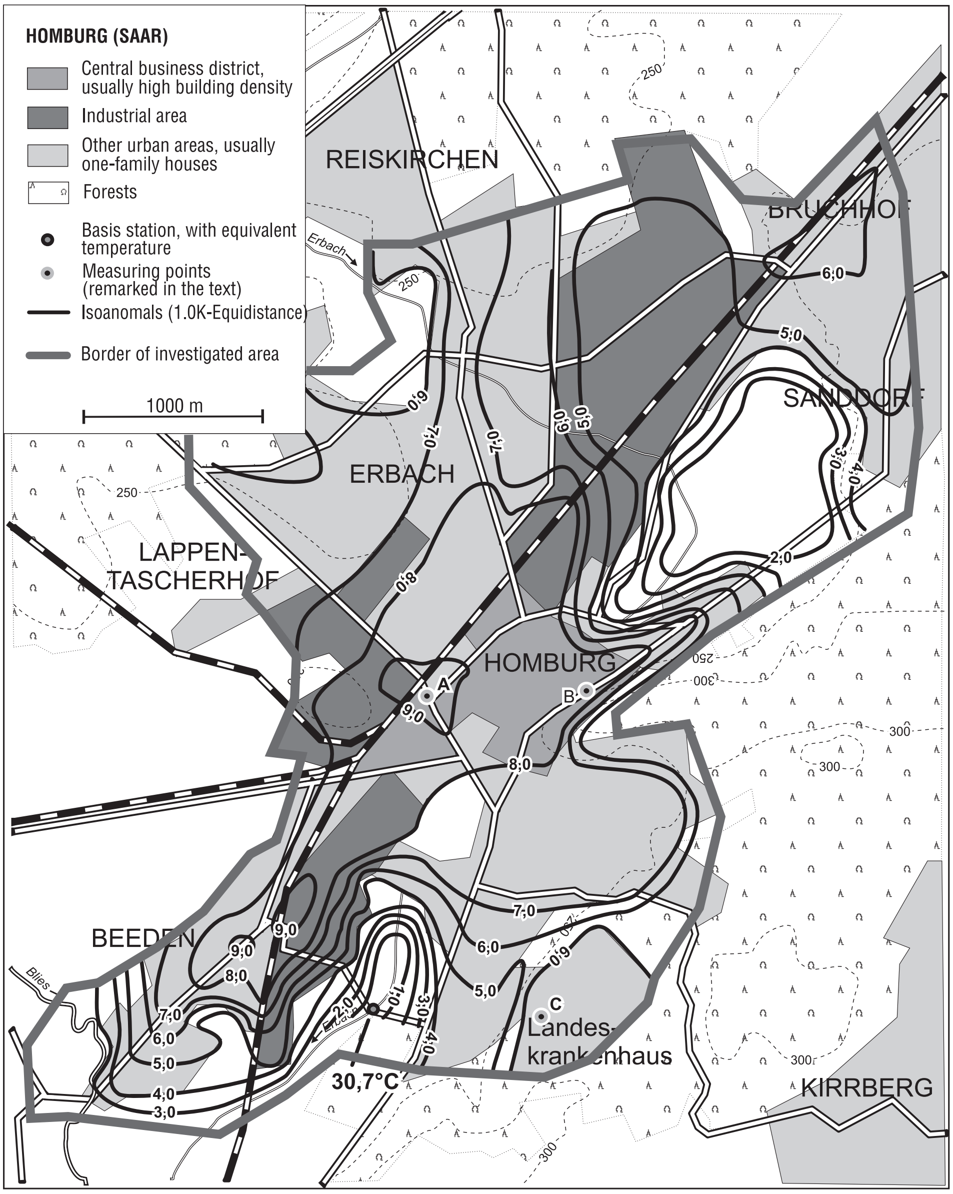

Fig. 1 Equivalent temperature distribution in the night 11/12 August, 1997, in Homburg, at windless and cloudless conditions

railway network (site A) and the western industrial area. The downtown and the adjacent city quarters are delimited by the isoanomaly 8K which is the line connecting the points of the same deviation from the given, assumed standard value. The area of the minimum equivalent temperature values is in the south, in the Erbach valley, and in the Closenbruch and the Blies valleys. There are two reasons behind the spatial differentiation of the equivalent temperature. The air temperature and specific humidity have overlapping ranges of the maximum and minimum values at night. It denotes that the maximum difference in the equivalent temperature in the studied area (9.3K), coincides with the maximum difference in the air temperature (5.6K). The air temperature in town, when compared with that of non-urban areas and especially with the areas consisting the reservoirs of the cold air in the Blies, Erbach and Closenbruch valleys, depends, i.a., on the input of heat of anthropogenic origin. When the relative humidity in these valleys is higher, the condensation of the water vapour occurs earlier. Thus, the content of water in the air decreases. On the other hand, in the built-up areas, the moisture in the air persists longer.

The described changes occur at night when the radiation is accompanied by weak wind gradients. From the bioclimatic standpoint it denotes that the air downtown in summer is more sultrily when compared with the non-urban areas. In the case described above, the thermal feeling ‘‘slightly cold’’ prevails in the non-urban areas and the feeling of ‘‘comfort’’ is reached in the downtown. However, other differences can appear as well. For example, if in the non-urban areas the feeling is ‘‘comfort’’ or ‘‘slightly sultrily’’ then in the town interior the feeling can be ‘‘sultrily’’. It should be emphasised that in the downtown area at the lower wind speed, the heat transport to the atmosphere is hindered which leads to the delayed cooling of the downtown location and negatively affects its climate. It should also be noted that the heat exchange between the interior of the buildings and the air in their surroundings might be hindered. It leads to a slower cooling of the houses and negatively affects the climate of the interiors in this way. In the downtown and old town built-up areas, the heat is gained by the humans due to direct solar radiation reaching the surface of the human bodies and the stream of heat escaping from the ground and the surroundings. The heat losses from the surface of human bodies depend on the turbulent exchange of the latent heat and on the long-wave radiation outgoing from the surface of the body and cloths (Kozłowska-Szczęsna et al. 1985). In the urban area, especially in the centres of large towns, the gains of heat usually prevail over the losses which, in the case of malfunctioning perspiration, leads to the less efficient thermoregulation of the body and, as a result, to overheating of the body (Lewińska 2000).

In Cracow (measurements at the night of 3/4 July, 1999), the maximum difference in the equivalent temperature between the urban and non-urban areas, despite the comparable meteorological conditions (the same season, no allochtonic wind, no cloudiness), was 16.8K (Fig. 2). The difference was much higher than in Homburg and was influenced by the difference in the size of the towns and the relief of both the towns.

The area of the maximum equivalent temperature is in the downtown area and is delimited by the isoanomaly 16.0K. The secondary maximum values of the equivalent temperature occur west of the downtown area, in the highly urbanised areas and east of

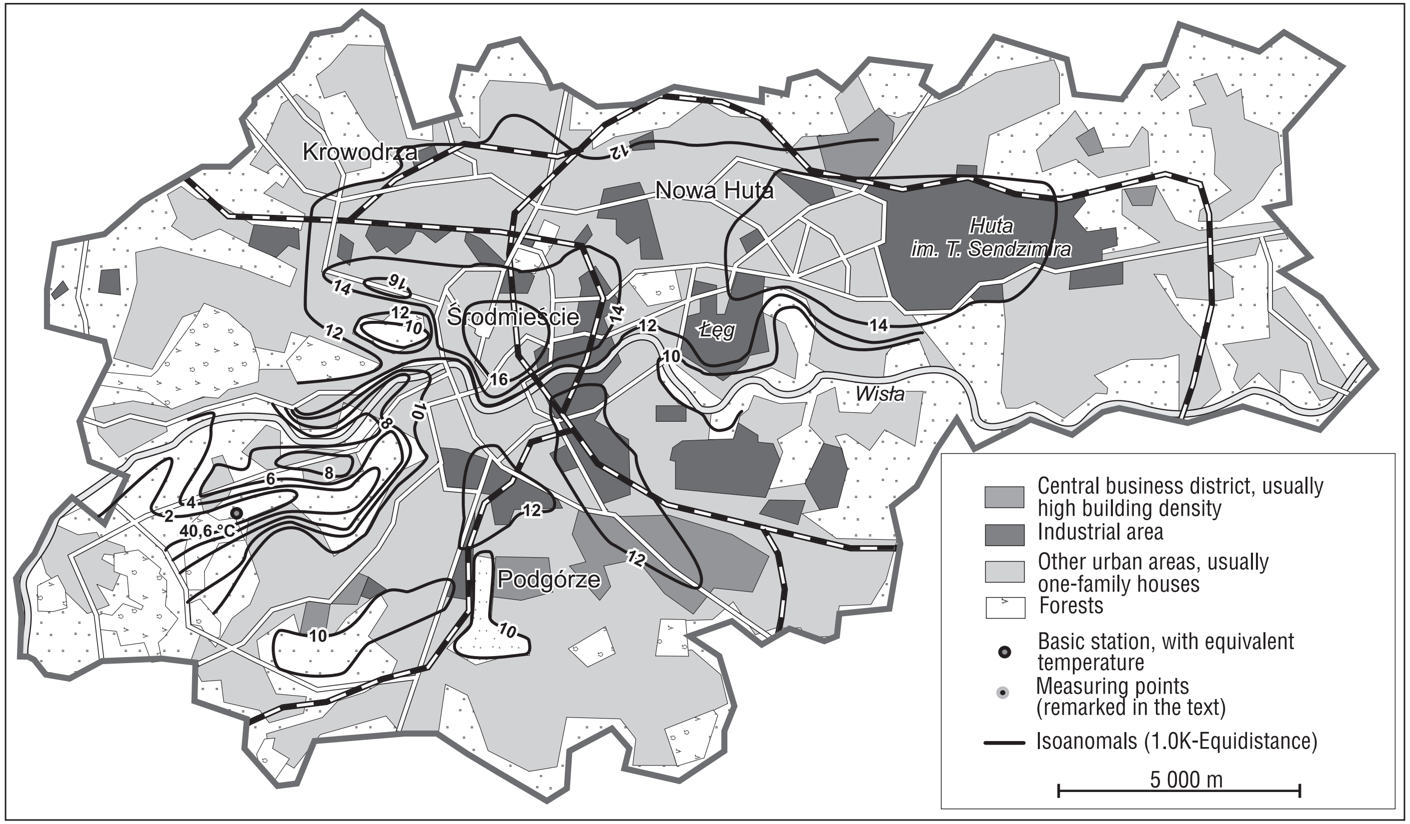

Fig. 2 Equivalent temperature distribution in the night 3/4 July, 1999, in Cracow, at windless and cloudless conditions

the town centre, in the industrial quarters of Nowa Huta and Podgórze. The area of the minimum equivalent temperature values is located in the southern part of Cracow, in the less urbanised regions with a low suburblike built-up area and in the cultivated valleys of the southern tributaries of the Vistula River. The spatial differentiation in the equivalent temperature is controlled by the distribution of the specific air humidity and air temperature. The high equivalent temperatures in the downtown are the consequences of the compact many-storied built-up area, multiple reflection of heat radiation between the houses as well as of the transformation of the stream of the atmospheric back radiation. In the Nowa Huta quarter the formation of the urban heat island is associated with heat emission from the Sendzimir Steel Works. As in Homburg, the accumulation of the cold air in the depressions and condensation of the water vapour contained in the air lead to the decrease of the equivalent temperature. The catabaticly cooled air flows into Cracow along the Vistula valley. The stream of this air is reinforced by the circulation between the town and its surroundings. In contrast to Homburg, the "sultriness" is felt more often and it is more intense in the downtown area of Cracow at nights. Whereas the equivalent temperature in the non-urban areas, especially in the reservoirs of cold air, can be felt as 'comfortable', then in the downtown areas and in the secondary urban heat islands the equivalent temperature reaches the interval of "sultriness" which reduces the feeling of well being and affects the health of the inhabitants.

4. Relationship between the equivalent temperature, wind speed and cloudiness

The spatial distribution of the equivalent temperature is not static but varies depending on the meteorological parameters such as wind direction and speed and cloudiness. To determine statistically the influence of these parameters on the equivalent temperature in Homburg, 226 field measurements along the established route were performed from June 1997 to May 1998.

The relationship between the maximum differences in the equivalent temperatures and wind speed in Homburg is presented in Fig. 3. The cloudiness during each measurement was additionally determined. In general, it can be stated that when the cloudiness and the wind speed increase in the examined area, the maximum differences in the equivalent temperatures successively decline.

When the maximum difference in the equivalent temperature in Homburg under conditions of a calm (no wind) and cloudless sky or only a slight cloudiness is still 10.0K, then at the cloudiness of 3/8 it decreases to 7.3K and when the sky is fully overcast, the maximum values reach 4.0K.

The situation is similar when the wind speed is higher and at the cloudiness as described above. It should be noted that at the low wind speed, the various degrees of cloudiness had a decisive influence on the extent of the maximum values of equivalent temperature. However, at the high wind speed this phenomenon did not always occur. At the wind speed > 3.5 $m \cdot s^{-1}$ at the base stations, the values are scattered in the range of 1.5K regardless of the degree of cloudiness.

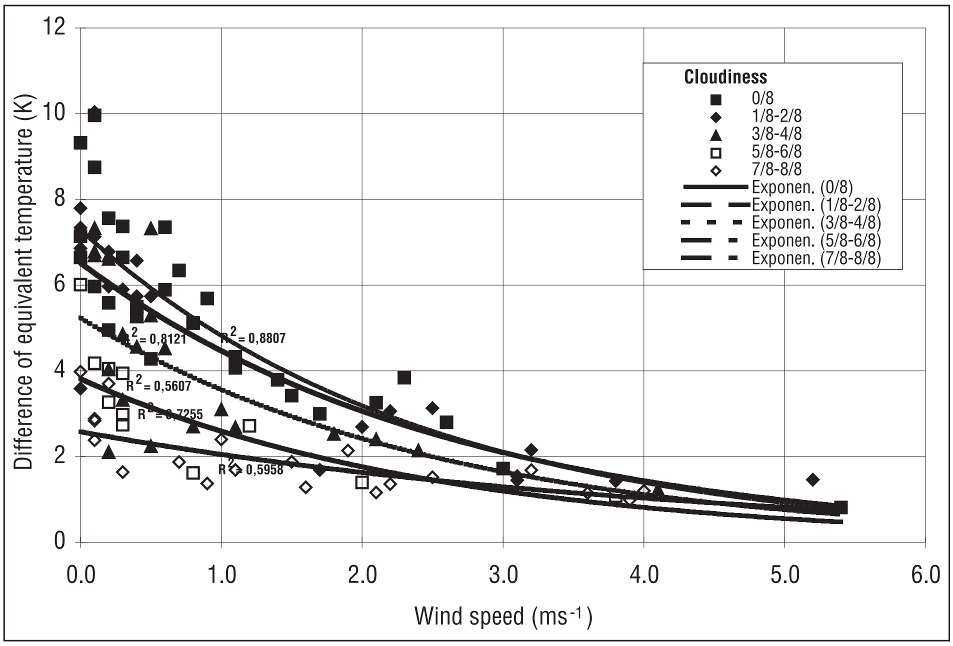

Fig. 3 Relation between maximum difference of equivalent temperature and wind speed at various cloudiness

5. Conclusions

It can be assumed that the bioclimate of the towns studied in this paper by the means of the equivalent temperature depends strongly on the surroundings. Generally, the maximum of the equivalent temperature at night occurs in the built-up downtown areas. In the industralised areas with the high thermal emission, the secondary maximum values can be identified. At noon no regularity was stated. Especially in the large towns (Cracow), the inhabitants might be more stressed by the higher sultriness. The studies in Homburg (the Saar Basin) in Germany have shown that the region of maximum values changes its extent, it "moves" towards the lee side as the wind speed increases but the region as such declines. Also with the increasing cloudiness one can state the decline in the differences in the equivalent temperature. In the seasonal distribution of the temperature there are characteristic the higher summer differences when compared with the non-urban areas. The difference in the equivalent temperature being higher in summer than in winter is unfavourable for the people living in towns.

The changes in the equivalent temperature in both the towns showed a similar tendency, and the differences were dependent on the size of the town and on the temporal changes. The studies, although of very short-duration in Cracow, and performed under radiation weather, have confirmed the influence of such factors as relief (concave and convex land forms, aspect and slope inclination), land use (open areas: farmland, forested areas, and of a built-up character: family houses, many–storied multifamilial housing estates, industrial areas).

References

Cena M., Gregorczuk M., 1966, *Rozkład temperatury ekwiwalentnej na obszarze Polski*, Roczn. Nauk Roln., 119, 191-211.

Flach E., 1957, *Grundbegriffe und Grundtatsachen der Bioklimatologie*, [in:] Baur F. Linkes Meteorologisches Taschenbuch. Bd. 3, Leipzig, 178-271.

Flach E., 1981, *Human bioclimatology*, [w:] H.E. Landsberg, *World survey of climatolog,. General Climatology*, 3, Els. Sc. Publ. Comp., Amsterdam-Oxford-New York, 2-187.

Kozłowska-Szczęsna T. (red.), 1985, *Metody badań bioklimatu człowieka*, Probl.Uzdrow., 1/ 2.

Kühne O., 1999, *Die Wetterlagen-Tages- und Jahreszeitabhängigkeit der Verteilung von Lufttemperatur, spezifischer Luftfeuchte, Windfeld, Äquivalenttemperatur und anderer bioklimatisch wirksamer Gröâen im Lokalklima der Stadt Homburg/Saar*, Dissertation zur Erlangung des akademischen Grades eines Doktors der Philosophie der Philosophischen Fakultät der Universität des Saarlandes, Saarbrűcken.

Landsberg H.E., 1981, *The urban climate*, New York, London, Toronto, Sydney, San Francisco.

Lewińska J., 2000, *Klimat miasta, zasoby, zagrożenia, kształtowanie,* IGPiK, Kraków.

Mydel R., 1994, *Rozwój urbanistyczny miasta Krakowa po drugiej wojnie światowej*, „Secesja", Kraków.

Zróżnicowanie temperatury ekwiwalentnej w mieście (na przykładzie Krakowa i Homburga)

Streszczenie

Temperatura ekwiwalentna jest uznawana za jeden z wyznaczników termicznego obciążenia organizmu człowieka. W latach 1997-1999 przeprowadzono pomiary patrolowe temperatury ekwiwalentnej w Krakowie (Polska) i Homburgu (Niemcy). Stwierdzono, że wskaźnik ten dobrze odzwierciedla różnice między stosunkami bioklimatycznymi w śródmieściu i w strefie pozamiejskiej. Zmiany temperatury ekwiwalentnej w obydwu badanych miastach wykazywały podobną tendencję, ich różnice zależały od wielkości miasta i zmian w czasie. Badania – choć bardzo krótkotrwałe w Krakowie, wykonane w warunkach pogody radiacyjnej, potwierdziły działanie takich czynników jak warunki rzeźby terenu oraz sposób zagospodarowania: tereny otwarte – rolnicze, zalesione, tereny zabudowy: mieszkaniowa jednorodzinna, wielorodzinna, tereny przemysłowe. Ogólnie maksimum temperatury ekwiwalentnej nocą występuje w gęsto zabudowanym śródmieściu. Na obszarach uprzemysłowionych o wysokiej emisji termicznej można zidentyfikować wtórne maksima. W południe nie udało się stwierdzić żadnej prawidłowości. Szczególnie w dużych miastach (Kraków) może być wyższe obciążenie parnością mieszkańców miasta. Badania w Homburgu – Zagłębie Saary, wykazały, że obszar maksimów nie utrzymuje się na stałym miejscu, to znaczy nie jest statyczny, lecz przesuwa się ku stronie odwietrznej, jednocześnie słabnąc ze wzrostem

prędkości wiatru. Również przy zwiększającym się zachmurzeniu można stwierdzić obniżanie się różnic temperatury ekwiwalentnej. W rozkładzie sezonowym temperatury występują charakterystyczne wyższe letnie różnice w stosunku do terenów pozamiejskich

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