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SELECTED EXAMPLES OF BIOCLIMATIC ANALYSIS APPLYING THE PHYSIOLOGICALLY EQUIVALENT TEMPERATURE IN HUNGARY

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Összefoglalás – Cikkünkben bioklimatológiai elemzést végzünk az ún. Fiziológiailag Equivalens Hőmérséklet (PET) index felhasználásával először Magyarország egész területén (1 km-es felbontású bioklíma térkép segítségével). A bioklíma térképek a PET index térbeli eloszlását mutatják Magyarországon egy téli (február) és egy nyári (augusztus) hónapban. Majd két szinoptikai állomás (Szombathely és Sopron) 1996 és 1999 között rögzített adataiból számított PET értékek alapján részletes elemzésben hasonlítjuk össze a két város főbb bioklimatológiai jellegzetességeit.

Summary – In this study, maps were created that show the geographical distribution of Physiologically Equivalent Temperature (PET) values in February and August for the area of Hungary, with a resolution of 1 km. For the further analysis of the thermal bioclimate, data of the synoptical stations of Szombathely and Sopron, recorded from 1996 to 1999, has been used. This study provides a detailed analysis and comparison of the bioclimatic properties of these locations.

Key words: Physiologically Equivalent Temperature, thermal comfort, mapping, Hungary

1. INTRODUCTION

For the bioclimatic evaluation of a specific location or area not only a single meteorological parameter is required, but a complex evaluation of the effects of climate conditions and thermo-physiological values in order to describe the effects of the thermal environment on humans. Several models and indices were developed to calculate the extent of thermal stress during the last decades. The earlier bioclimatic indices (Discomfort Index, Windchill, thermohygrometric index-THI) consider only some meteorological parameters (*Thom,* 1959; *Steadman,* 1971; *Unger,* 1999; *Matzarakis et al.*, 2004). Recent models, based on the human energy balance equation, produce so-called comfort indices - for example Predicted Mean Vote-PMV, Physiologically Equivalent Temperature-PET, Outdoor Standard Effective Temperature-OUT_SET* - to evaluate the thermal stress and thermal comfort on the human body (*Fanger,* 1972; *Jendritzky et al.*, 1990; *Höppe,* 1993, 1999; *VDI*, 1998; *Matzarakis et al.*, 1999; *Spagnolo and de Dear,* 2003). These indices can be applied in different time and spatial resolutions for recent climate and climate change projections (*Jendritzky et al.*, 1990; *Matzarakis et al.*, 1999; *Koch et al.*, 2005; *Matzarakis*, 2006). For example, describing a small area (eg. the surroundings of a building, part of a street), with fine resolution can be useful for architects and urban designers (*Mayer and Matzarakis*, 1998; *Matzarakis,* 2001). Micro-scale studies (eg. bioclimatological description of a town) provide data for urban planning (*Unger et al.*, 2005). Examining even larger areas (eg. a whole region or country) has not only scientific value: the results of these studies can form the basis of planning regional recreation and tourism development (*Mayer and Matzarakis*, 1997; *Matzarakis et al.*, 1999; 2004; 2007; Matzarakis, 2006).

The aim of this study is to present a bioclimatic analysis of Hungary by means of bioclimatic mapping with the aid of geo-statistical methods. The present study links geographical information (*Hastings et al.*, 1999) with climatological data (*New et al.*, 1999, 2000, 2002) in order to generate a spatial distribution of PET values of a region. The calculation of PET is performed with the application of the RayMan Model, which calculates the thermal indices mentioned above (*Matzarakis et al.*, 2000, 2007).

2. STUDY AREA AND METHODS

2.1. Study area

Although the original study was carried out for a larger area, this paper focuses on the description of bioclimatic properties in Hungary (the national border is marked with black line – *Fig. 1*).

Hungary is situated in the Carpathian Basin almost in the centre of Europe between the latitudes 45°48’N and 48°35’N, longitude 16°05’E and 22°58’E with an areas of 93,030 km^2.

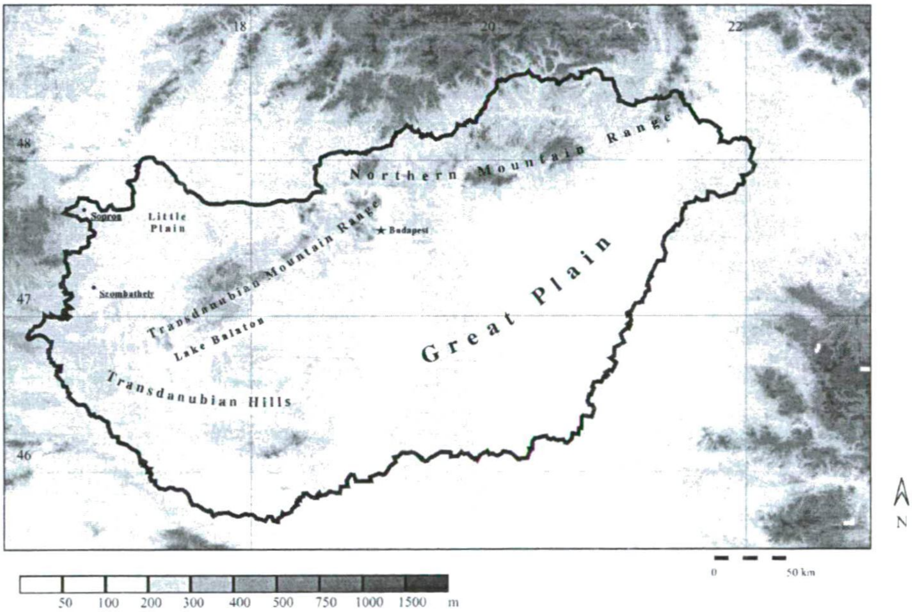

Fig. 1 Geographical location and topography of Hungary (the numbers are northern latitudes and eastern longitudes in degrees) and location of the two examined cities

As *Fig. 1* shows Hungary has three basic relief types: the low-lying regions (under 200 m above sea level) of the Great Plain in the east, centre and south-east, and of the Little

Plain in the north-west, which together cover the two-thirds of Hungary's territory. There is the Northern Mountain Range (Északi-középhegység); and the mountainous (Transdanubian Mountain Range - Dunántúli-középhegység) and hilly regions of Transdanubia in the west and south-west (Transdanubian Hills - Dunántúli-dombság).

The main characteristics of Hungary's climate and the frequent fluctuations in climatic factors are greatly due to the central position in Europe. Namely, Hungary is situated at the 'crossroads' of the East-European continental, the West-European oceanic and the subtropical Mediterranean climatic zones (*Pécsi and Sárfalvi*, 1964).

Using Köppen's classification, Hungary fits in the climatic region *Cf*, which is characterized by a temperate warm climate with a rather uniform annual distribution of precipitation. Its annual mean temperature is 10.4°C (in Budapest/Lőrinc); the amount of precipitation is 516 mm. These values show little variance across the country due to the limited variation in topography (*WMO*, 1996).

2.2. *Applied bioclimatic index*

In this study one of the most widely used bioclimatic indices, the PET is used, as it has a widely known unit (°C) as an indicator of thermal stress and thermal comfort (*Table 1*). This makes the results easily comprehensible for potential users. This is especially the case for planners, decision-makers, and even the public who might not be familiar with modern human-biometeorological terminology. PET evaluates the thermal conditions in a physiologically significant manner (*Höppe,* 1999; *Matzarakis et al.,* 1999).

Table 1 Physiologically Equivalent Temperature (PET) for different grades of thermal sensation and physiological stress on human beings (during standard conditions: heat transfer resistance of clothing: 0.9 clo internal heat production: 80 W) (*Matzarakis and Mayer*, 1996)

PET (°C)	Thermal sensation	Physiological stress level
	very cold	extreme cold stress
4	....	....
	cold	strong cold stress
8	....	....
	cool	moderate cold stress
13	....	....
	slightly cool	slight cold stress
18	....	....
	comfortable	no thermal stress
23	....	....
	slightly warm	slight heat stress
29	....	....
	warm	moderate heat stress
35	....	....
	hot	strong heat stress
41	....	....
	very hot	extreme heat stress

PET is defined as the air temperature at which the human energy budget for the assumed indoor conditions is balanced by the same skin temperature and sweat rate as under the actual complex outdoor conditions to be assessed.

PET enables various users to compare the integral effects of complex thermal conditions outside with their own experience indoors (*Table 1*). In addition PET can be used throughout the year and in different climates (e.g. *Mayer and Matzarakis*, 1997; *Höppe*, 1999). Meteorological parameters influencing the human energy balance, such as air temperature, air humidity, wind speed and short- and longwave radiation, are also represented in the PET values. PET also considers the heat transfer resistance of clothing and the internal heat production (*VDI*, 1998).

2.3. The RayMan model

One of the recently used radiation and bioclimate models, RayMan, is well-suited to calculate radiation fluxes (e.g. *Mayer and Höppe*, 1987; *Matzarakis*, 2002; *Matzarakis et al.*, 2007), and thus, all our calculations for T_{mrt} and PET were performed using this model. The RayMan model, developed according to the Guideline 3787 of the German Engineering Society (*VDI*, 1998) calculates the radiation flux in simple and complex environments on the basis of various parameters, such as air temperature, air humidity, degree of cloud cover, time of day and year, the albedo of the surrounding surfaces and their solid-angle proportions.

The main advantage of RayMan is that it facilitates the reliable determination of the microclimatological modifications of different urban environments, since the model considers the radiation modification effects of the complex surface structure (buildings, trees) very precisely. Besides the meteorological parameters, the model requires input data on the surface morphological conditions of the study area and on personal parameters.

2.4. Data

The used climate data for this analysis was provided by the data collation program at the Climatic Research Unit (*New et al.,* 1999, 2000, 2002). The required data for the thermal bioclimate analysis – these are air temperature, relative humidity, sunshine and wind speed – are available at monthly resolution for the climate period 1961 to 1990 at ten minute spatial resolution for the specific area. The calculated PET grid values have been used as dependent variable. They have been recalculated into a higher spatial resolution (1 km) through the use of geo-statistical methods (independent variables were latitude, longitude and elevation). For this purpose the digital elevation data of the GLOBE data set (*Hastings et al.,* 1999) was used.

An additional analysis has been performed for two selected stations (Szombathely and Sopron) for the period 1996 to 1999 for 12 UTC in order to describe the thermal bioclimate conditions more analytically on a daily basis.

3. RESULTS

3.1. Spatial distribution of PET in Hungary

From the produced monthly and seasonal maps, only one for the winter period (February), and one for the summer period (August) are presented here. The statistical relationship is very high ($r > 0.9$) for all months and seasons.

The spatial distribution of the average PET in February for the period of 1961-1990 is shown in *Fig. 2.* The orographical situation of Hungary is not diverse: most of the country lies on plains below 200 m latitude, thus the bioclimatic conditions are relatively homogeneous. The whole country is categorised as being subject to extreme cold stress levels. The regional differences are not more than 9°C. The lowest PET values (-9°C) can be observed in the areas with higher latitude, especially in the Northern Mountain Range. Due to the effect of the oceanic climatic zone, the winter is milder in Transdanubia. This is the main reason why the PET values are not so low (between -4 and -6°C) in the Transdanubian Mountain Range as in the Northern Mountain Range (between -6 and -9°C).

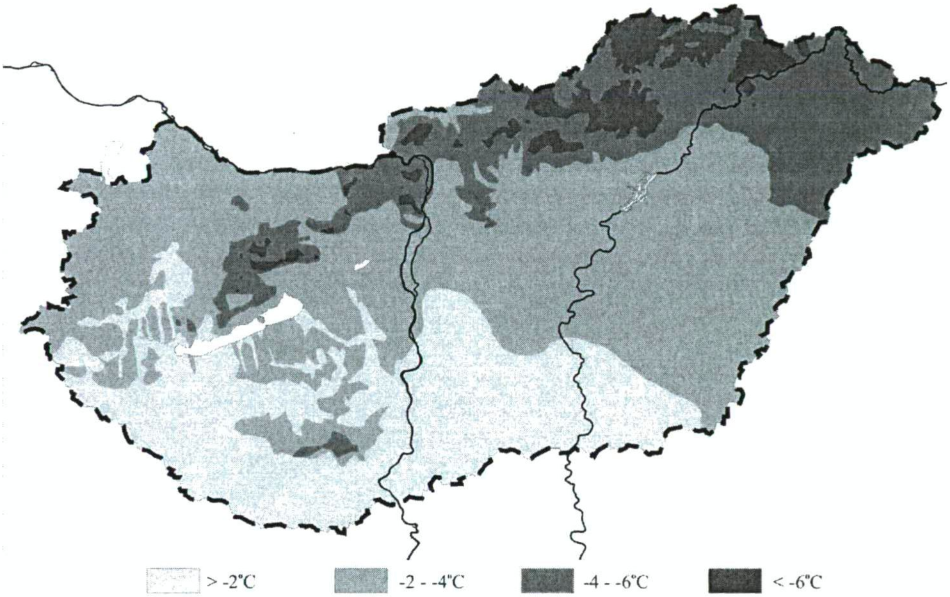

Fig. 2 Geographical distribution of PET for February

The cold stress in February is less pronounced in the southern part of the Great Plain and in the Transdanubian Hills, due to the mediterranean effect in case of the latter. Towards the eastern borders of the country, the PET values are decreasing due to the increasingly continental (and Carpathian) climate. The cold stress increases in the hill regions, and it has the lowest value in the Northern Mountain Range.

Fig. 3. shows the spatial distribution of the average PET values for August during the examined time frame. The ΔPET is higher in this month than in February (11–7°C) and covers three stress levels (*Table 1*). In August, however, the bioclimatic situation in the plains is more homogeneous than in February. There is a maximum PET value of 26°C, dominating the south-western part of the country, reaching upwards in the Duna, Tisza, and Dráva valley. Almost the whole country has average PET values, corresponding to the "slightly warm" category. The thermal sensation decreases below 23°C only in the hill regions, and further decreases by one physiological stress level at the higher altitudes (*Table 1.*). The PET values are decreasing in the mountains to the "slightly cool" thermal sensation (PETmin = 14°C).

It should be noted that the coastline of Lake Balaton, one of Hungary's most popular tourist destination, shows the lowest cold stress level in February. The situation is different in summer, when the heat stress is high around the lake, especially on the north-western coast which is surrounded by mountains. This situation, which is caused by the southern exposure and the reflection from the water surface, creates ideal circumstances for water-based recreational activities.

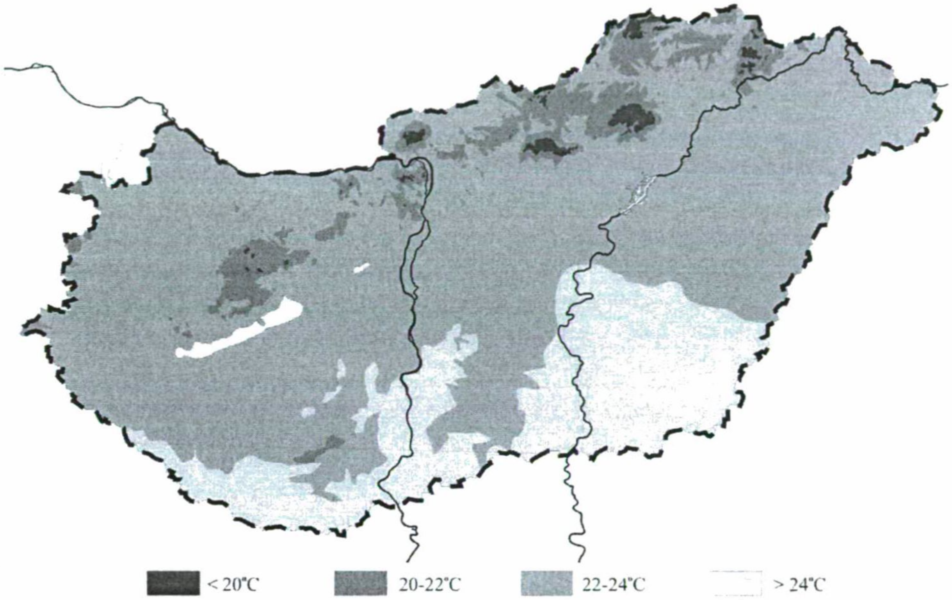

Fig. 3 Geographical distribution of PET for August

3.2. Selected stations

An additional analysis that has been performed with the PET index, based on daily meteorological values of a certain location, provides an opportunity for a more detailed analysis of the bioclimatic situation of the two selected areas. The chosen two meteorological stations (Szombathely and Sopron) are located close to the western border of the country in proximity to the Alps at about 210 m above the sea level, approximately 50 km from each other. Their climate conditions are strongly affected by the proximity of the Alps and characterised by the oceanic effect throughout the year.

The bioclimatic diagrams for the two places (*Fig. 4*) illustrate information on the percentages of different bioclimatic classes of PET, plotted in decas (10 days intervals) during the whole year, based on a four-year long data series for 12 UTC in the period of 1996-1999.

The diagram also shows the following values:

- mean PET value in the examined time period (PETa)
- maximum PET value in the examined time period (PETmax)
- minimum PET value in the examined time period (PETmin)
- amount of days for the examined period with PET < 0°C, 15°C < PET < 25°C and PET > 35°C.

The characteristics of the bioclimatic properties of the two examined cities are obviously similar but differences can be easily detected.

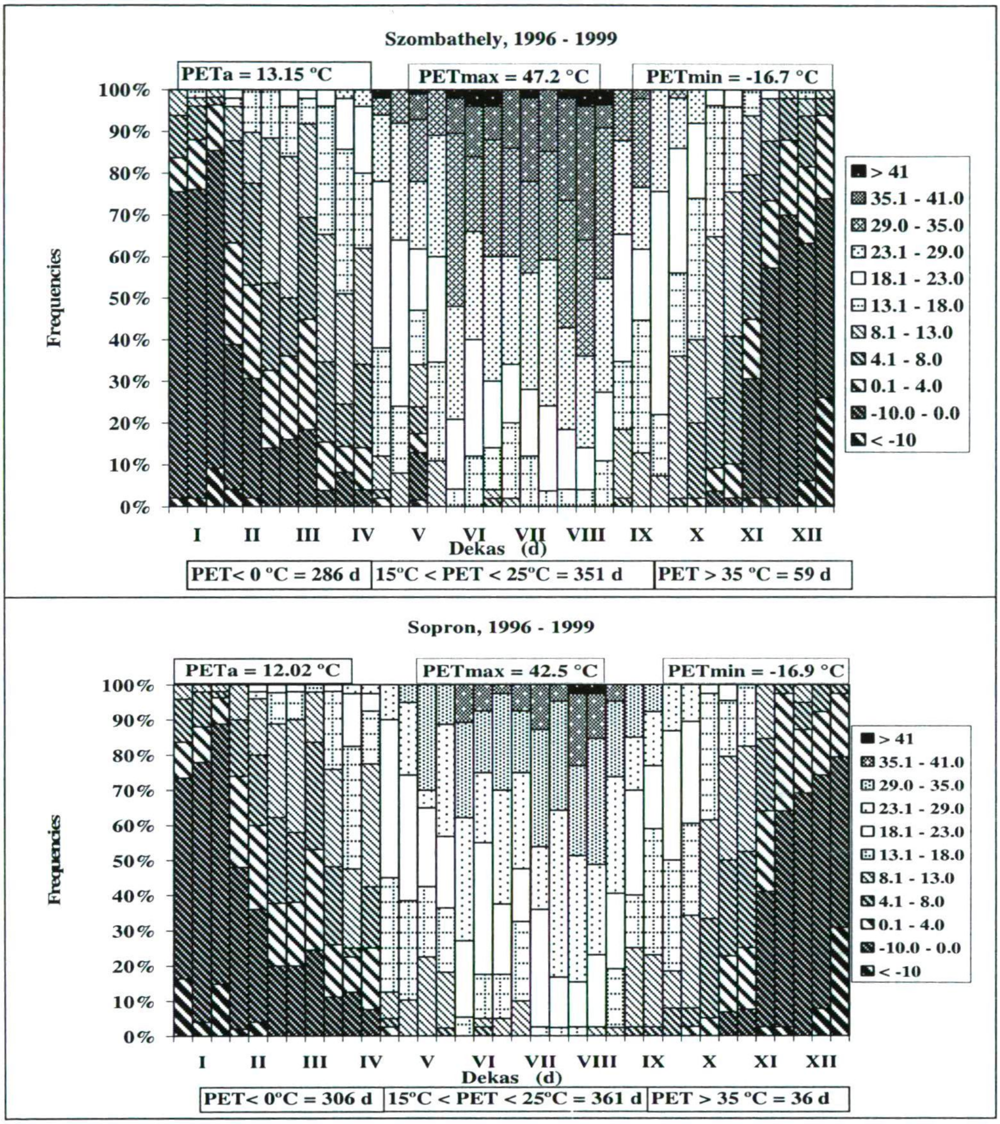

Fig. 4 Bioclimate diagram for Szombathely and Sopron for 1996 to 1999 for 12 UTC

The climate data obtained for Hungary show that January has the lowest average mean temperature (*WMO*, 1996). However, the lowest PET values (most extreme cold stress) were calculated with the highest probability in both cities in December and January. Despite that the PET values of the examined cities are nearly identical (PETmin_{Szh}: -16.7°C, PETmin_{So}: -16.9°C), the occurrence of PET > 0°C value is approximately 10% lower in Szombathely. Comfortable, heat stress-free periods occur at higher probability in the second half of April in both cities (again later in the second half of September). Interestingly, the frequency of the occurrence of these comfort periods was slightly lower in Szombathely than in Sopron (Szh = 351 days, So = 361 days), during the examined period.

The bioclimatic profile of Szombathely is warmer and shifted to the higher heat stress, compared to Sopron. Common feature is that the first days with moderate and strong heat stress (PET > 29°C) occurred in spring; heat stress becomes even more intense in May. (However, the occurrence of PET > 29°C value is approximately 30% higher in Szombathely, than in Sopron.) The possible reason for this phenomenon is the increasing continental effect that occurs in the Carpathian Basin, resulting in shortened transitional seasons (spring and autumn). This effect cannot be masked by the western location of the examined meteorological station. The frequency of the days with strong and extreme heat stress (PET > 35°C) is constantly increasing during the summer months and reaches the highest values in the first decas of August. In Szombathely, however, extreme heat stress days can be observed form the second half of April and the occurrence of these days is more frequent until the end of August than in Sopron. The amount of days with PET > 35°C for the examined period is in Szombathely 59 and in Sopron just 30, thus the number of days with extreme heat stress was nearly two times higher in Szombathely than in Sopron. The difference of the maximum of the PET values is higher than in the case of the minimum values ($\text{PETmax}_{\text{Szh}}$: 47.2°C, $\text{PETmax}_{\text{Szh}}$: 42.5°C). The bioclimatic data clearly show the presence of several days with comfortable thermal sensation in early autumn ("Indian Summer"). This "Indian Summer" is more pronounced in Szombathely than in Sopron: it is longer and has higher PET values.

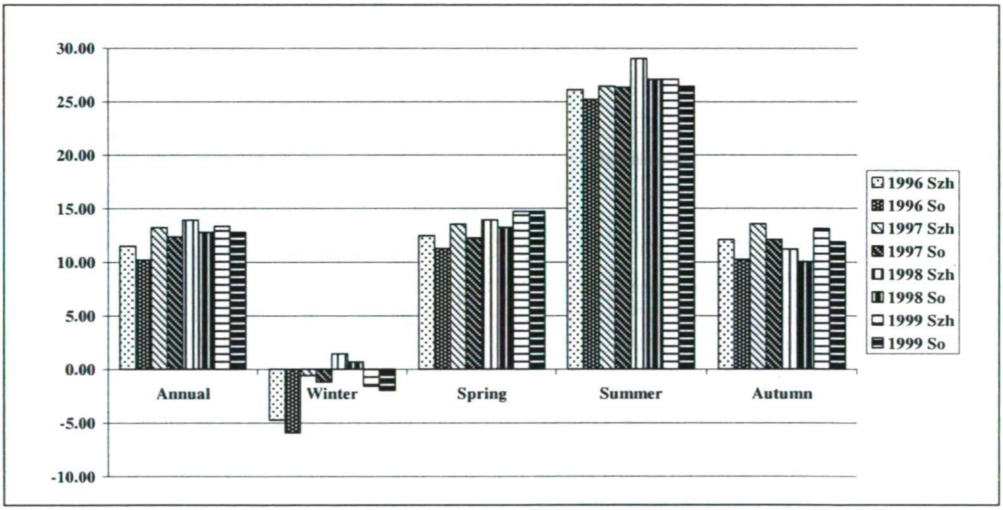

Fig. 5 Annual and seasonal average PET values in Szombathely (Szh) and Sopron (So) between 1996-1999, 12 UTC

The annual average PET value is higher by 1.13°C in the case of Szombathely than in Sopron. *Fig. 5* shows the annual and seasonal averages of the PET values.

Differences between the two examined locations, despite the close location and same elevation, can be observed. The main reason of this can be the stronger effect of the mountains in Sopron, which shifts its climate to a colder range in a bioclimatic sense.

4. CONCLUSIONS

Spatial data are required in order to describe and analyse the bioclimate of regions or areas. The methods exist, and the thermal indices based on the energy balance of humans present an appropriate method.

Bioclimate maps can be produced by using existing gridded data and geo-statistical methods of mesoscale and microscale resolution for a region. When applying a time resolution of several months, it is impossible to discover the whole range of thermal bioclimate conditions, especially in extreme events. Extreme conditions can be analysed through the use of data from synoptical or climatological networks.

Because of the used ten-day intervals, which are more detailed than monthly resolutions and also more relevant for recreation and tourism, the presented bioclimate diagram constitutes a highly effective method.

For the bioclimate of Hungary the produced maps present a first approach in the field of high resolution maps, which can be helpful for diverse issues like human health and tourism. Additionally, periods of extreme cold and heat waves can now be detected.

The climate becomes more continental towards north, north-east throughout the country. This is represented in the bioclimatic properties of the examined area: the thermal stress tends towards extremities both in summer and winter.

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