Influence of land cover / land use changes on urban heat island: Case study of Bratislava

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1. Introduction

The climate warming trend and city growth contribute to generation of excessive heat in urban areas (Zuvela-Aloise et al. 2016). Temperature may markedly increase especially in urban heat islands (UHIs) and consequently negatively afflict the quality of life in the cities. The term UHI refers to the atmospheric warmth of a city compared to the countryside. Stewart and Oke (2012) argue that extra warmth of cities has some practical implications, for example in cities with a relatively cold climate the heat island may convey cheaper house heating costs. However, UHIs in relatively hot climates potentially raise the threat of heat stress and mortality as well as the cost of air conditioning. It is the reason why researchers concentrate on tracking and assessment of the impact of the expanding urban coverage and the land taken by residential buildings, industrial and power constructions, motorways, roads and parking lots along. They explore and assess changes in micro- and mezzo-climatic conditions in built-up areas.

Recently, numerical modelling has come to represent an opportunity leading to more detailed and more accurate information about the spatio-temporal variability of urban air temperatures and UHI parameters (Mills 2009; Geletič et al. 2016). The current state of the art of numerical models makes it possible to solve the thermodynamics of the atmosphere and complex relations between variables, such as the height of buildings and the structure of buildings, used materials, height and types of vegetation on the scale of urban environment.

The objective of the presented paper is to introduce the first results of project *Effect of impermeable soil cover on urban climate in the context of climate change* (on an example of Bratislava) supported by the Slovak Research and Development Agency (SRDA) along with its following partial aims:

- Identification and analysis of urban coverage rate and the causes of their change exemplified by Bratislava the capital of Slovakia by application of satellite data and the Geometric Base of the National Infrastructure of Spatial Data (ZB GIS®) and those obtained by field measurement and research,
- Analysis and assessment of different types of urban fabric and its change depending on the changing temperature regime in the quoted city by application of the MUKLIMO (Microscale Urban Climate Model) model,
- Cartographic presentation of obtained results to be used by local administration and other potential users.

2. Study area

The Bratislava study area (Fig. 1) is situated in the south-west part of Slovakia bordering Austria in the west and Hungary in the south. This area is identical with functional urban area (FUA) Bratislava delineated in terms of the project Urban Atlas (UA). Bratislava is the capital of Slovakia, the country's largest city and its political, cultural and economic centre. Due to this fact and a good quality transport infrastructure, it is a territory with high potential for territorial development. The limiting factor for further expansion of the city is the Malé Karpaty mountain range located north of the city centre. Bratislava lies on the both banks of the Danube River, which crosses the city from the west to the south-east. The population of the capital city Bratislava by the end of 2015 was 422,453 (7.78% of the population in Slovakia). Based on the analysis of the Sentinel-2A satellite image acquired in August 2015 (Vatseva et al. 2016), impervious surfaces, urban vegetation, and water covered 51.6%, 46.5%, and 1.9% of the territory respectively. According to the 15-class nomenclature of urban green spaces – UGS (Rosina and Kopecká 2016), the largest part was represented by class *Urban greenery in family housing areas* i.e. in total more than 20% of the urban greenery. UGS defined as *Urban greenery in apartment housing areas* covered the second largest area i.e. 13.2% of UGS. However, this class was represented by the highest number of patches (823 out of total 2,909 UGS polygons). The urban area of Bratislava has significantly increased in recent twenty years due to building of the new automobile plant Volkswagen. Anthropogenic modifications of the landscape and relatively rapid increase of impervious surfaces represent critical driving forces increasing the UHI effects.

3. Data and methods

The non-hydrostatic MUKLIMO (In German: Mikroskaliges Urbanes KLIma MOdell) model has been developed for microscale urban climate and planning applications (Sievers and Zdunkowski 1986). It further provides a tool for various scientific applications on the urban scale (e.g. urban flow, cold air drainage, urban heat islands). The model MUKLIMO uses high-resolution orography, land cover / land use (LC/LU) distribution data and the temperature, humidity and wind characteristics in the vertical profile of the atmosphere (up to 1 km above ground level). The model outputs may be used to study the development of the air and surface temperature and air humidity field, but also for quantification of the effect of relief, LC/LU and weather conditions on urban climate. This model is also useful for the UHIs analysis and assessment. The "cuboid method" (Zuvela-Aloise et al. 2014) can be applied for assumption of possible climate changes in urban heat load under future climate conditions, i.e. expected increase in the number of summer days (with maximum temperature ≥ 25 °C).

Urban climate is an outcome of complex interactions between atmospheric processes and LC/LU and land forms. Arnfield (2003) in his review of long-term urban climate research stresses the fact that most studies suggest significant differences in the relationship between LU and UHI intensity. Oke (2004) designed a simple and generic classification of city zones to improve sitting of meteorological instruments in urban areas. His scheme divides city terrain into seven homogenous regions called "urban climate zones" (UCZs), which range from semi-rural to intensely developed sites. Most recently, Loridan and Grimmond (2011) developed "urban zones for characterizing energy partitioning", or UZEs. Their classes were defined by threshold values for the active vegetative and built surface fractions of cities. In some European countries, the "climatope" system has been used to classify urban terrain and urban climates, especially for planning purposes (e.g. Wilmers 1991; Scherer et al. 1999). However, Steward, Oke (2012) argue that a system that excludes rural landscapes is not well suited to heat island investigation, nor is the one with class names and definitions that are culture or region specific. These authors defined local climate zones (LCZs) as regions of uniform surface cover, structure, material, and human activity that span from hundreds of meters to several kilometres in horizontal scale. The LCZs are represented by 10 built-up classes and 7 other LC classes. This scheme has become a standard for the description of the environment in the field of urban climate research and LU classes were defined on the basis of LCZs that were used to model spatio-temporal variability of air temperature by MUKLIMO (Geletič et al. 2016; Skarbit, Gál 2016).

LCZs in the project *Effect of impermeable soil cover on urban climate in the context of climate change* were replaced by more detailed LC/LU classes, the results of the UA 2012 project, and adapted for the application in this project (Tab. 1). Areas of the UA classes were identified by interpretation of the SPOT 4/1998, SPOT 5/2007, Sentinel 2/2016 satellite images and completed by the ZB GIS® (heights of buildings and the parking areas) data as well as the data about urban greenery (with prevalence of tree vegetation, prevalence of grass vegetation and prevalence of mixed tree/grass vegetation) also obtained by interpretation of the above-mentioned satellite images. Fig. 2 brings the applied LC/LU classes identification. The minimum size of surface of identified areas is 1 ha and their minimum width is 20 m. From the point of view of content these are classified into 53 classes (from which only 44 classes were identified in the territory of Bratislava) first of all of urbanised landscape (by intensity of impermeable surfaces in a span of less than 10% to 80% and more and the height of buildings), farming landscape, forest and semi-natural landscape, wetland areas and waters (see Tab. 1). Areas of these classes identified for the years 1998, 2007 and 2016 represent the input data for the MUKLIMO model.

Original layers were adjusted for the purposes of MUKLIMO model. The five digits code from extended nomenclature of the UA 2012 (see Tab. 1) was used to distinguish between 53 LC/LU classes created for the FUA Bratislava. Several attributes of the LC/LU classes were needed:

– Building density is defined as ratio between built-up area and whole area of LC/LU classes.
– Wall area index (WAI) (Deutscher Wetterdienst 2014) is computed by following equation:

$$WAI = h\,\frac{2\,(a+b)}{a \times b},$$

where h is building height, a and b represents its length and width.

For the computation of building density and WAI the layer of buildings from Open Street Map was adopted. Herein QuickOSM-plugin in QGis software was used to obtain the data in vector format. For this layer the tool *Summarize within* in ArcGIS Pro software was used to establish mean geometry of buildings. The data about building heights and imperviousness were derived from class description in extended nomenclature of the UA 2012; the mean values of the used interval were selected. The LC/LU layer was converted into raster format. LU table was created in order to connect the codes of local climate zones used for the map with their attributes. Except the ratio of built-up area and WAI, the data about imperviousness, building heights, tree heights and vegetation canopy properties were attached to LU table. Meteorological inputs are stored in *muklimo.in* file. Here the temperatures, air humidity, wind speed and direction from Bratislava-Airport meteorological station were used. For vertical profile of air temperature and humidity the aerological measurements from the nearest aerological station Wien, Hohe Warte were used. Another supplementary attributes were used in the input including water temperature, soil type, temperature, and humidity. Digital elevation model was gained by resampling of 90 meters SRTM model (Jarvis et al. 2008) into 100 meters pixel size. The date 11 of June 2015 was selected as the modelling day for the model with three LC/LU settings (1998, 2007 and 2016 – see Fig. 3). The reason for choosing this day was the existence of field temperature measurements in various parts of the city which were carried out for the purpose of UHI assessment and model validation.

4. The MUKLIMO_3 output fields and the air temperature comparison between the years 1998, 2007 and 2016

NetCDF – file was used for the visualization of MUKLIMO_3 output fields. It contains different variables such as air temperature in 2 meters above ground, relative humidity, wind velocity, etc. The researched area is 256 square kilometres in case of the FUA Bratislava. MUKLIMO_3 output fields present selected meteorological variables in daily course. It creates a detailed spatial-temporal overview of the development of atmospheric UHI in the FUA Bratislava. According to the UA 2012 extended nomenclature about 200 areas of LC/LU changes (Fig. 4) were observed in the FUA Bratislava between the years 1998–2016 in relation to population and urban sprawl. More built up area and less vegetated area in general cause serious changes in temperature conditions in the city. Increasing trend was detected in the mean air temperature in 84% cases of LC/LU changes in the FUA Bratislava (Fig. 5). On the other hand, 16% cases have had a decreasing trend between the years 1998–2016 (Fig. 5). Fig. 6 illustrates spatial distribution of temperatures of the FUA Bratislava for 11 June 2015. The higher density of built up areas and changes of forest or urban vegetated areas into the artificial concrete surface result in warming in the average by about +0.3 °C.

Tab. 1 – Land cover/land use nomenclature (extended Urban Atlas 2012 nomenclature, Meirich 2008).

1. Artificial surfaces
1.1 Urban fabric
1.1.1 Continuous urban fabric – sealing degree > 80%
1.1.1.1.0* Building height ≤ 5 m
1.1.1.2.0* Building height 5.1–10 m
1.1.1.3.0* Building height 10.1–15 m
1.1.1.4.0* Building height 15.1–20 m
1.1.1.5.0* Building height > 20 m
1.1.1.6.0* Different height of buildings
1.1.2 Discontinuous urban fabric – sealing degree ≤ 80%
1.1.2.1 Discontinuous dense urban fabric – sealing degree = 51–80%
1.1.2.1.1* Building height ≤ 5 m
1.1.2.1.2* Building height 5.1–10 m
1.1.2.1.3* Building height 10.1–15 m
1.1.2.1.4* Building height 15.1–20 m
1.1.2.1.5* Building height > 20 m
1.1.2.1.6* Different height of buildings
1.1.2.2 Discontinuous medium density urban fabric – sealing degree = 31–50%
1.1.2.2.1* Building height ≤ 5 m
1.1.2.2.2* Building height 5.1–10 m
1.1.2.2.3* Building height 10.1–15 m
1.1.2.2.4* Building height 15.1–20 m
1.1.2.2.5* Building height > 20 m
1.1.2.2.6* Different height of buildings
1.1.2.3 Discontinuous low density urban fabric – sealing degree = 11–30%
1.1.2.3.1* Building height ≤ 5 m
1.1.2.3.2* Building height 5.1–10 m
1.1.2.3.3* Building height 10.1–15 m
1.1.2.3.4* Building height 15.1–20 m
1.1.2.3.5* Building height > 20 m
1.1.2.3.6* Different height of buildings
1.1.2.4 Discontinuous very low density urban fabric – sealing degree ≤ 10%
1.1.2.4.1* Building height ≤ 5 m
1.1.2.4.2* Building height 5.1–10 m
1.1.2.4.3* Building height 10.1–15 m
1.1.2.4.4* Building height 15.1–20 m
1.1.2.4.5* Building height > 20 m
1.1.2.4.6* Different height of buildings
1.1.3.0.0* Isolated structures
1.2 Industrial, commercial and transport units
1.2.1 Industrial, commercial, public, military, private areas
1.2.1.1.0* Schools, hospitals, shopping areas and administrative facilities
1.2.1.2.0* Areas of production and warehouses
1.2.2 Road and railway networks and associated land
1.2.2.1.0* Fast transit roads and associated land
1.2.2.2.0* Other roads and associated land
1.2.2.3.0* Railways and associated land
1.2.3.0.0* Port areas
1.2.4.0.0* Airports
1.3 Mine, dump and construction sites
1.3.1.0.0* Mineral extraction and dump sites
1.3.3.0.0* Construction sites
1.3.4.0.0* Land without current use
1.4 Artificial non-agricultural vegetated areas
1.4.1.0.0* Green urban areas
1.4.2.0.0* Sport and leisure facilities
2. Agricultural areas
2.1.0.0.0.0 Arable land – annual crops
2.2.0.0.0.0 Permanent crops
2.3.0.0.0.0 Pastures
2.4.0.0.0.0 Complex and mixed cultivation patterns
2.5.0.0.0.0 Orchards
3. Forest (natural and plantation) + Semi-natural areas
3.1.0.0.0.0 Forests
3.2.0.0.0.0 Herbaceous vegetation association
3.3.0.0.0.0 Open space with little or no vegetation
4.0.0.0.0.0 Wetlands
5.0.0.0.0.0 Water

*means that the class includes one of three types of vegetation:
class code+1 – woody vegetation prevails outside sealed area,
class code+2 – grass vegetation prevails outside sealed area;
class code+3 – mixed vegetation (trees and grass) prevails outside sealed area;
class code+0 – class with no vegetation.

Minimum mapping unit is 1 ha and minimum width of a linear polygon (e.g. roads, railways, rivers) is 20 m.

Fig. 1 – Location of the study area (marked by the red square).

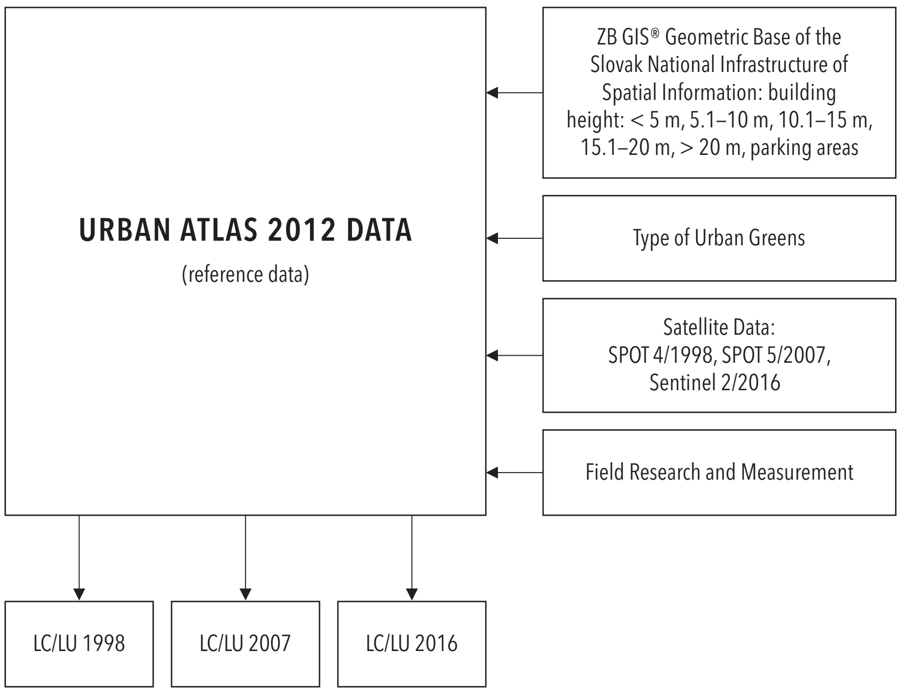

Fig. 2 – Flowchart of the identification of LC/LU classes for 1998, 2007 and 2016.

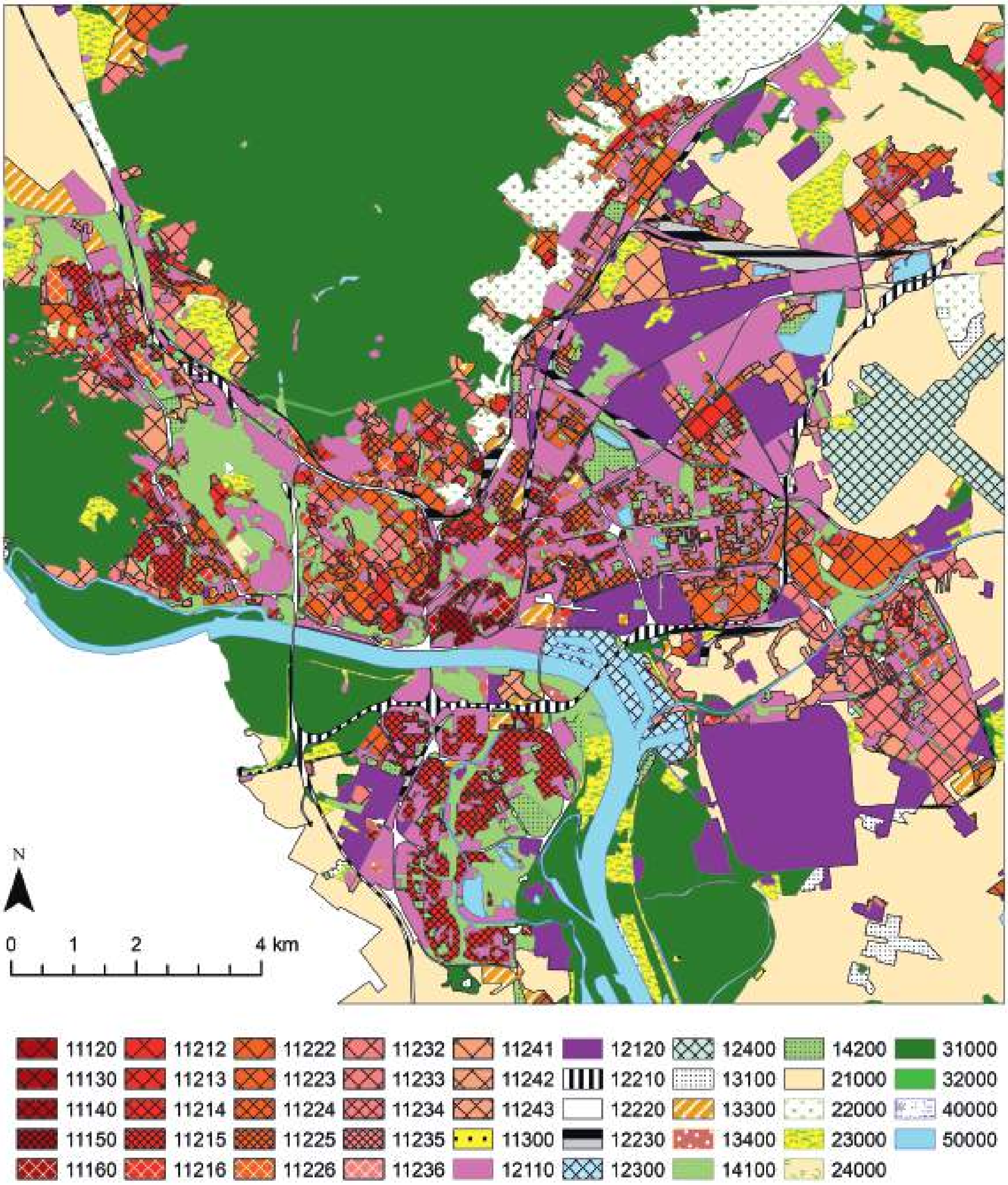

Fig. 3 – Spatial distribution of 44 LC/LU classes of the FUA Bratislava for the year 2016. The five-digit codes are explained in Tab. 1.

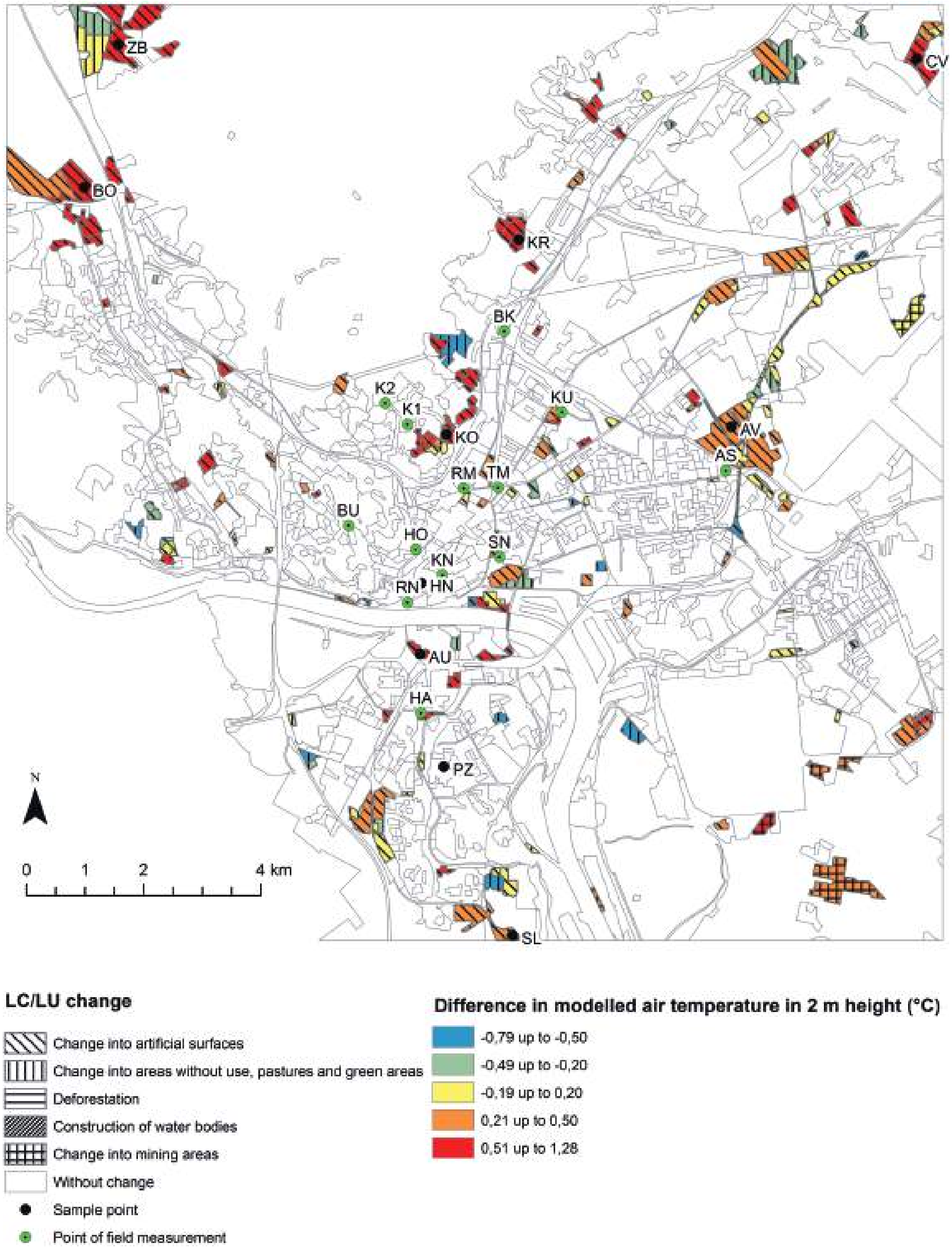

Fig. 4 – Difference in modelled air temperature in 2 m height (°C) within changes of LC/LU classes between 1998 and 2016 for modelled day, 11 June at 12:00 CET.

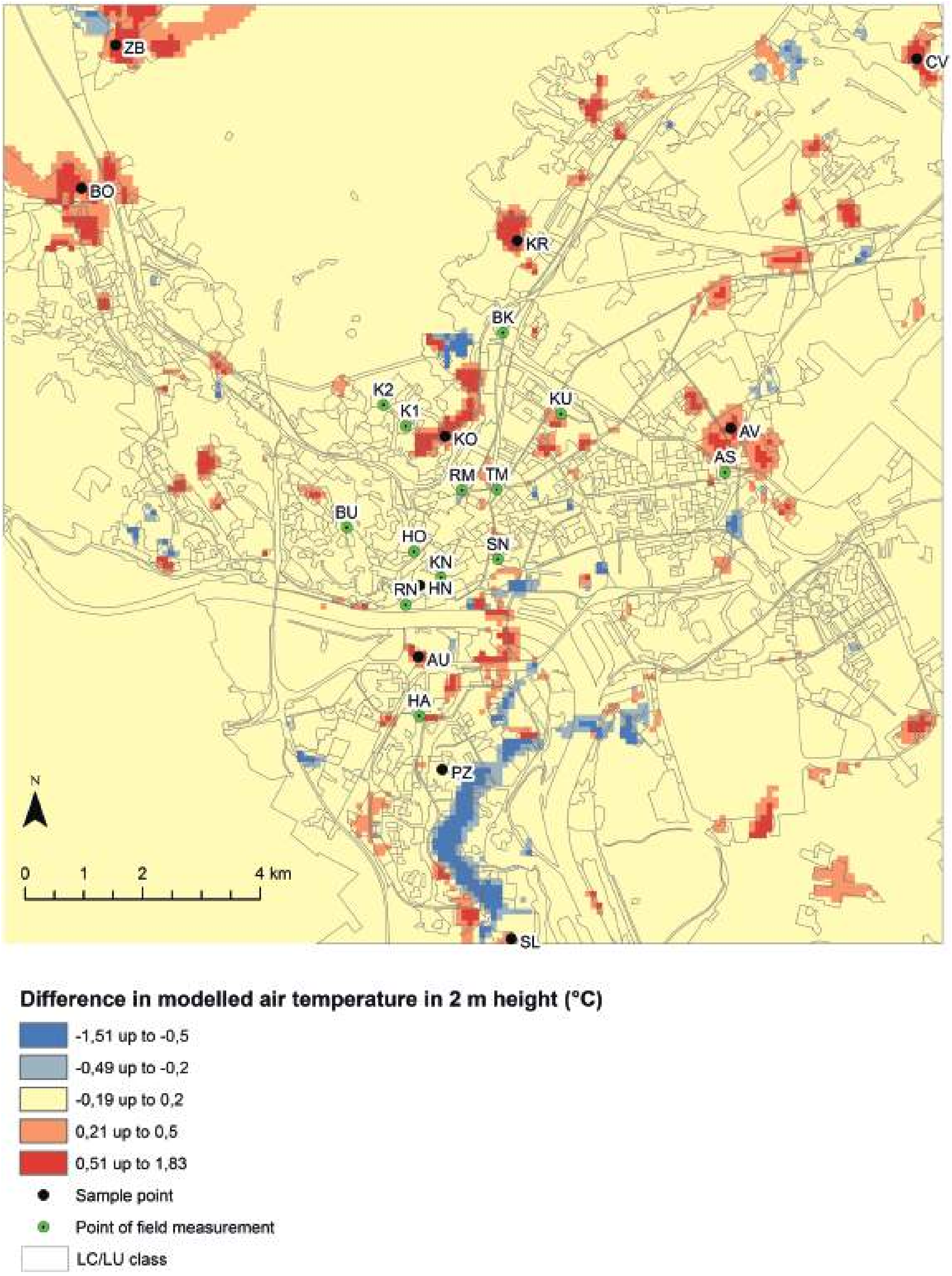

Fig. 5 – Difference air temperature in 2 m height (°C) in gridded format between 1998 and 2016 for modelled day, 11 June 2015 at 12:00 CET.

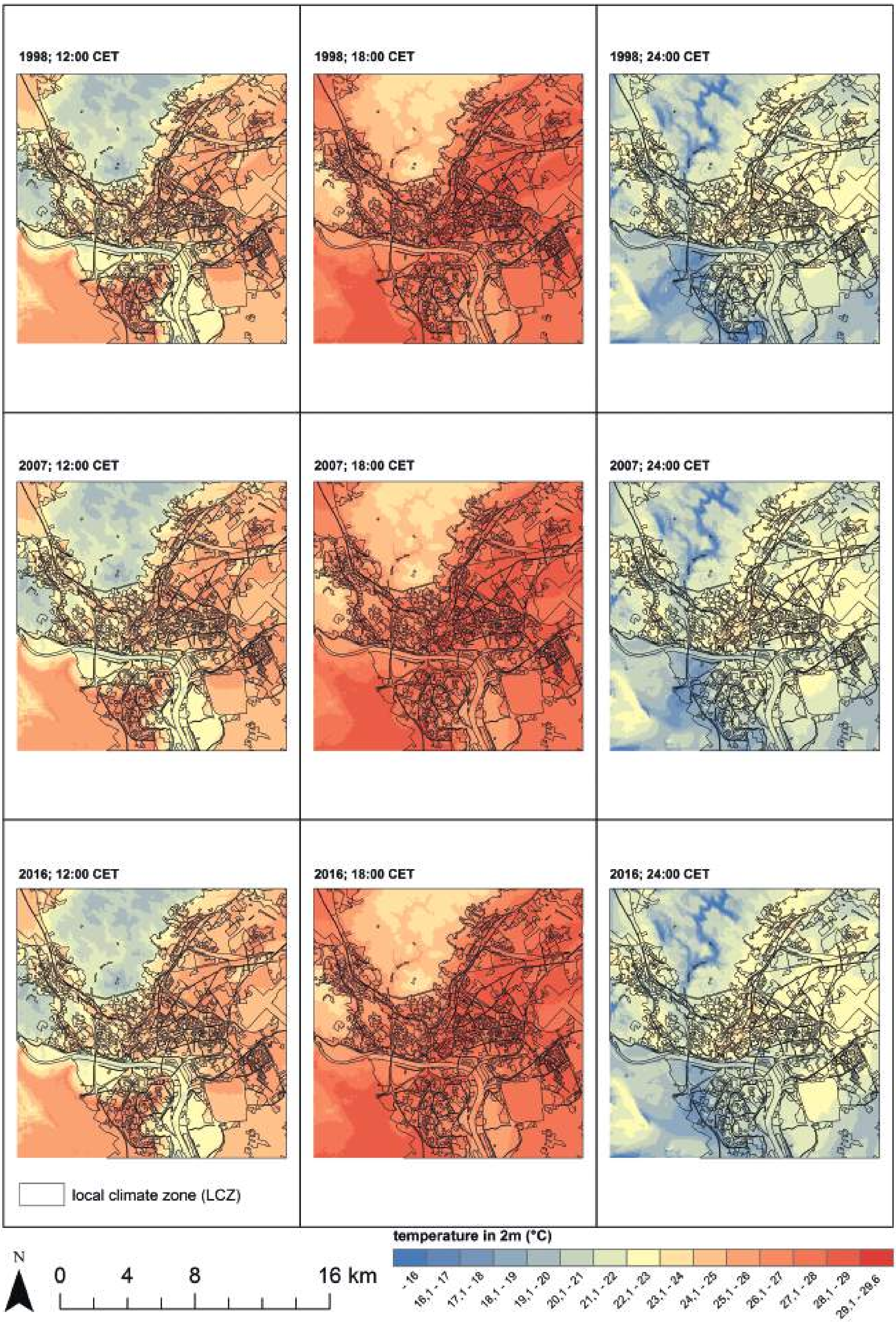

Fig. 6 – Spatial distribution of temperatures of the FUA Bratislava with LC/LU classes from 1998, 2007 and 2016 for modelled day, 11 June 2015 at 12:00, 18:00 and 24:00 CET.

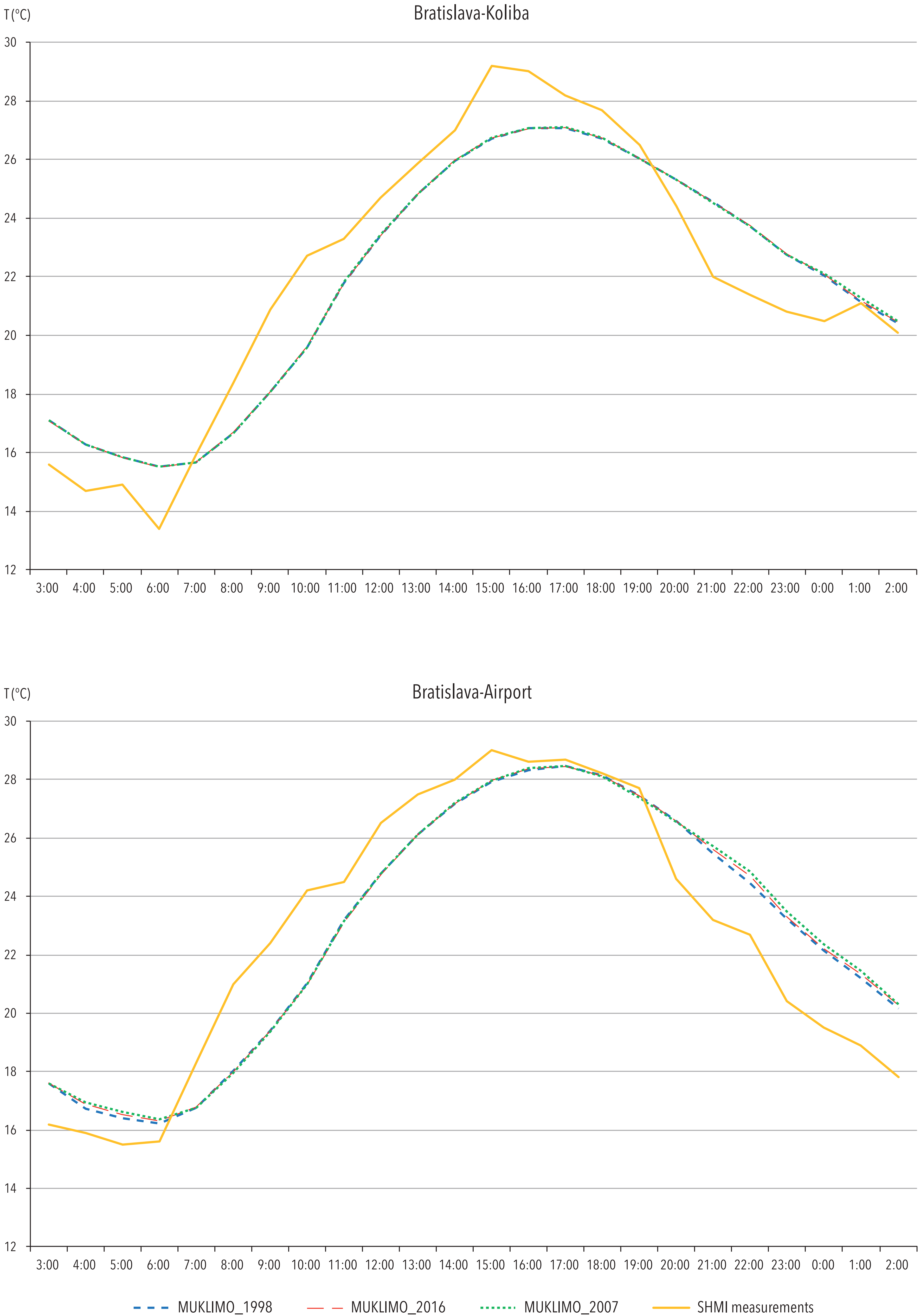

Fig. 7 – Comparison of modelled temperatures for years 1998, 2007 and 2016 and real measurements in two regular climatologic stations Bratislava–Airport and Bratislava–Koliba for modelled day, 11 June 2015.

The large industrial areas from the socialist era (1948 to 1989), vineyards and fruit groves that ran wild and became overgrown by vegetation are cooler in the average by about −0.2 °C. Localities with various types of LC/LU changes were selected for comparision of daily temperature course between 1998, 2007 and 2016 (Fig. 8). The highest positive temperature anomalies, even +0.9 °C are on the south-eastern slopes at the foothill of the Malé Karpaty Mountains with permanent crops (22000) in 1998 and a dense urban fabric (11222) in 2016 in the Krasňany (KR) municipality. Another example is the conversion of arable land (21000) into discontinuous dense urban fabric (11212) in suburban district Chorvátsky Grob – Čierna Voda (CV) where mean air temperature increased by +0.7 °C in the period 1998–2016. We also point out a serious LC/LU and air temperature changes in Petržalka (PZ) municipality. One of the biggest commercial and shopping centres in Bratislava (12110) – Aupark (AU), occupied green urban areas (14100) and air temperature increased by +0.6 °C in the average. The opposite situation with negative air temperature anomalies appeared in the area of Apollo refinery (12120) where vegetation overgrew the ruins (13400). The cooling effect of vegetation is −0.5 °C compared to the years 1998–2016. Except localities with LC/LU change, some areas remain in the same conditions, e.g. Hlavné námestie Square (HN), because of no changes in architecture, built up density and greening (Fig. 8). These examples confirm that vegetation plays an important role in the city centre where it may mitigate overheating. It can improve the environment for city residents rapidly.

5. MUKLIMO_3 output fields verification

Two regular climatologic stations, Bratislava-Airport and Bratislava-Koliba, were available for the validation of the output data (Fig. 7). In addition, employees of Slovak Hydrometeorological Institute conducted special measurements for the purpose of urban climate research during the modelled day (11 June, 2015) at 13 sample points in Bratislava (Fig. 9). We had real measured data from 15 points (13 sample points + 2 regular climatologic stations) available for the comparison. Modelled values overestimate minimum air temperature and underestimate maximum daily temperature in general. Despite of this fact the modelled values show satisfactory results. Climatologic station Bratislava-Airport is cooler by −0.13 °C in daily average based on the model in comparison with the year 2016. On the other hand, station Bratislava-Koliba is warmer by +0.16 °C. The field measurements coincide very well with the modelled data too. The best fitted are those from Hodžovo námestie Square (HO), Astronomická Street (AS) and Koliba – Slovak Hydrometeorological Institute (K1). The worst results are from Rybné námestie Square (RN) and Biely Kríž Square (BK). In comparison with the modelled data between the years 1998, 2007 and 2016 we observe a typical daily course of urban heat island in areas with radical land use changes of vegetated areas or arable land into densely populated urban structures or large commercial areas. In case of the Avion (AV), Bory Mall (BO) and Aupark (AU) shopping centres the increase of air temperature is obvious.

6. Conclusions

Urban areas are among those most endangered by the potential global climate changes. Therefore, the studies concerning the impact of global changes on local climate of cities are of high significance for the urban inhabitants' health and wellbeing. In order to plan and undertake the mitigation actions in particular cities, it is necessary to recognize the possible range of heat increase and its spatial extent.

Because of the progress achieved in exploring the complexity of processes driving the climate system, models designed for application on the city scale have gradually been developed.

Presented approach documented identification of LC/LU classes as the input data for MUKLIMO_3 model in order to assess UHIs in FUA Bratislava.

Obtained results showed that the MUKLIMO_3 model affects spatial – temporal variability of the air temperature in the FUA Bratislava (during 11 June 2015) caused by LC/LU changes suitably.

Simulation of temperatures is planned for additional days to obtain longer series of modelling, and cities Trnava and Žilina will be included in the modelling as well.

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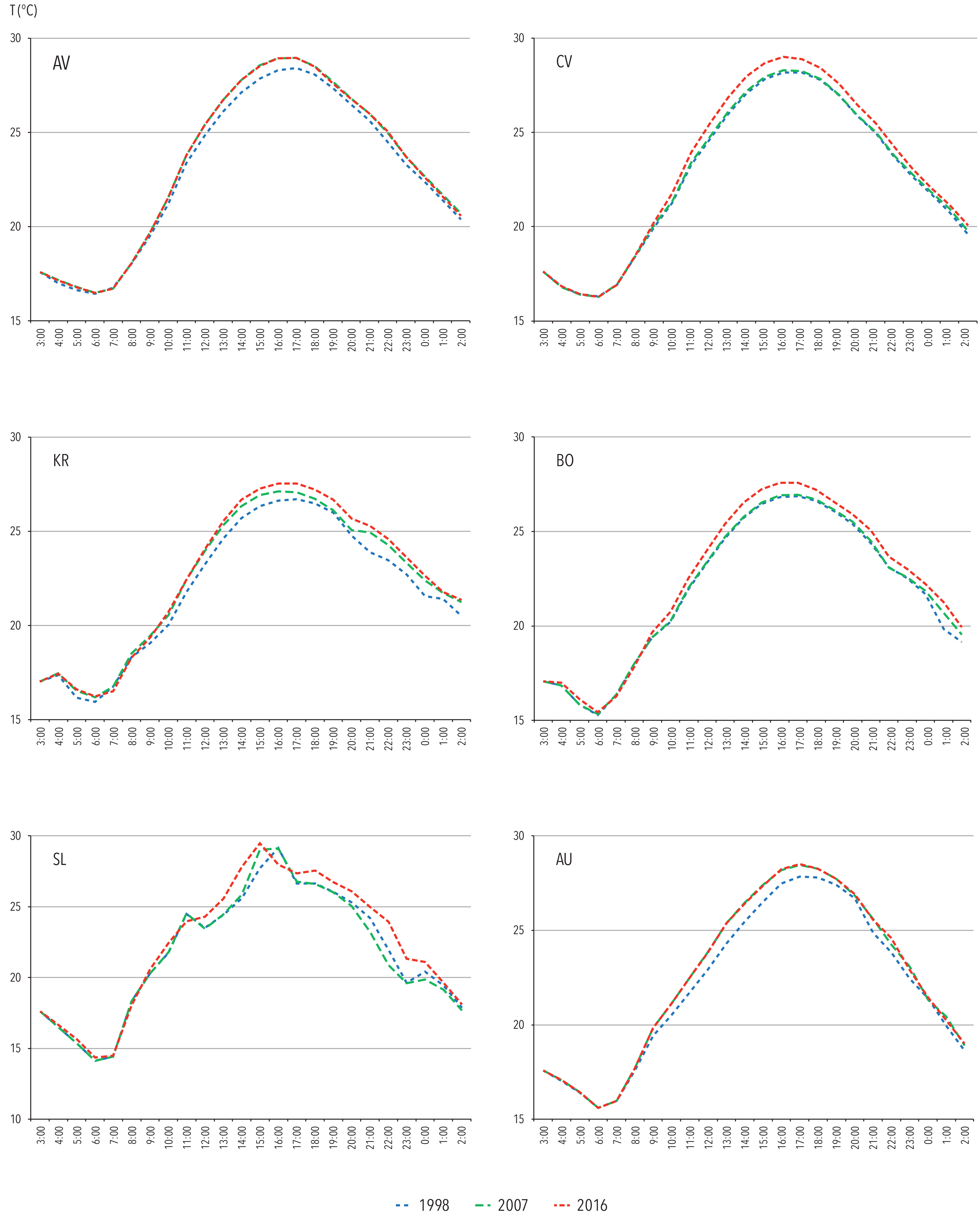

Fig. 8 – Comparison of time series modelled temperatures for years 1998, 2007 and 2016 in the FUA Bratislava for modelled day, 11 June 2015.

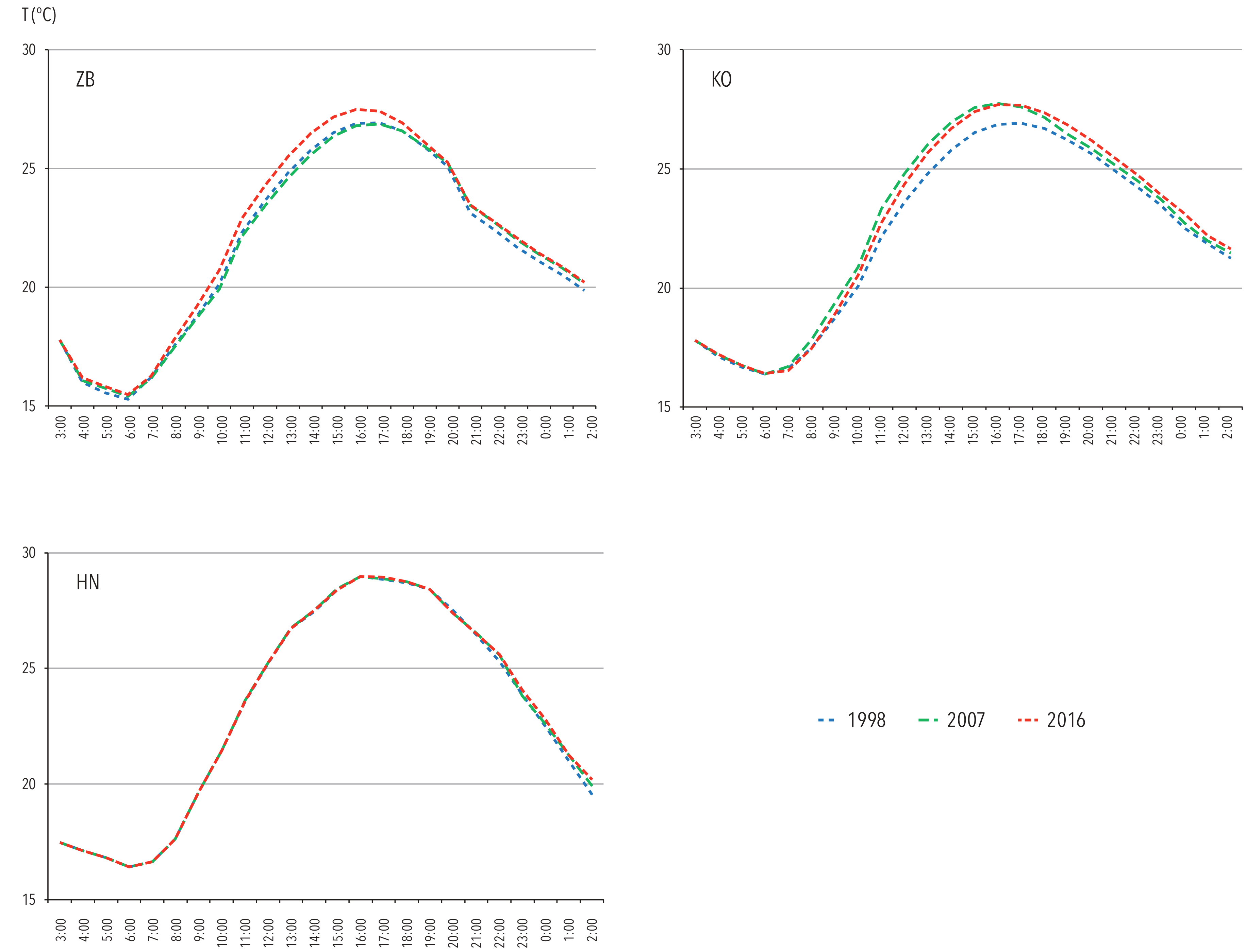

Fig. 8 (continued) – Comparison of time series modelled temperatures for years 1998, 2007 and 2016 in the FUA Bratislava for modelled day, 11 June 2015.

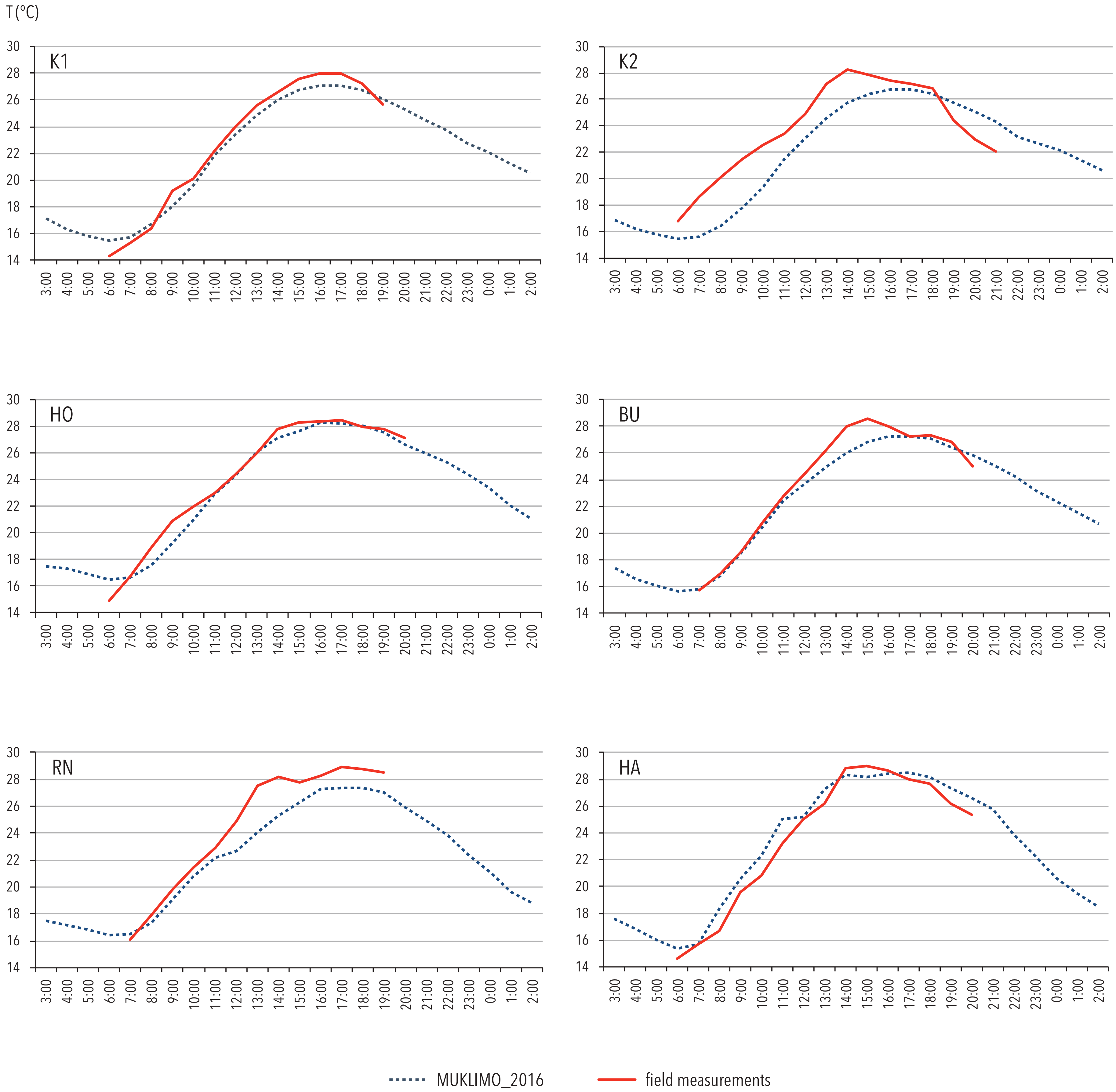

Fig. 9 – Comparison of modelled temperatures and real measurements in 13 sample points in the FUA Bratislava for modelled day, 11 June 2015.

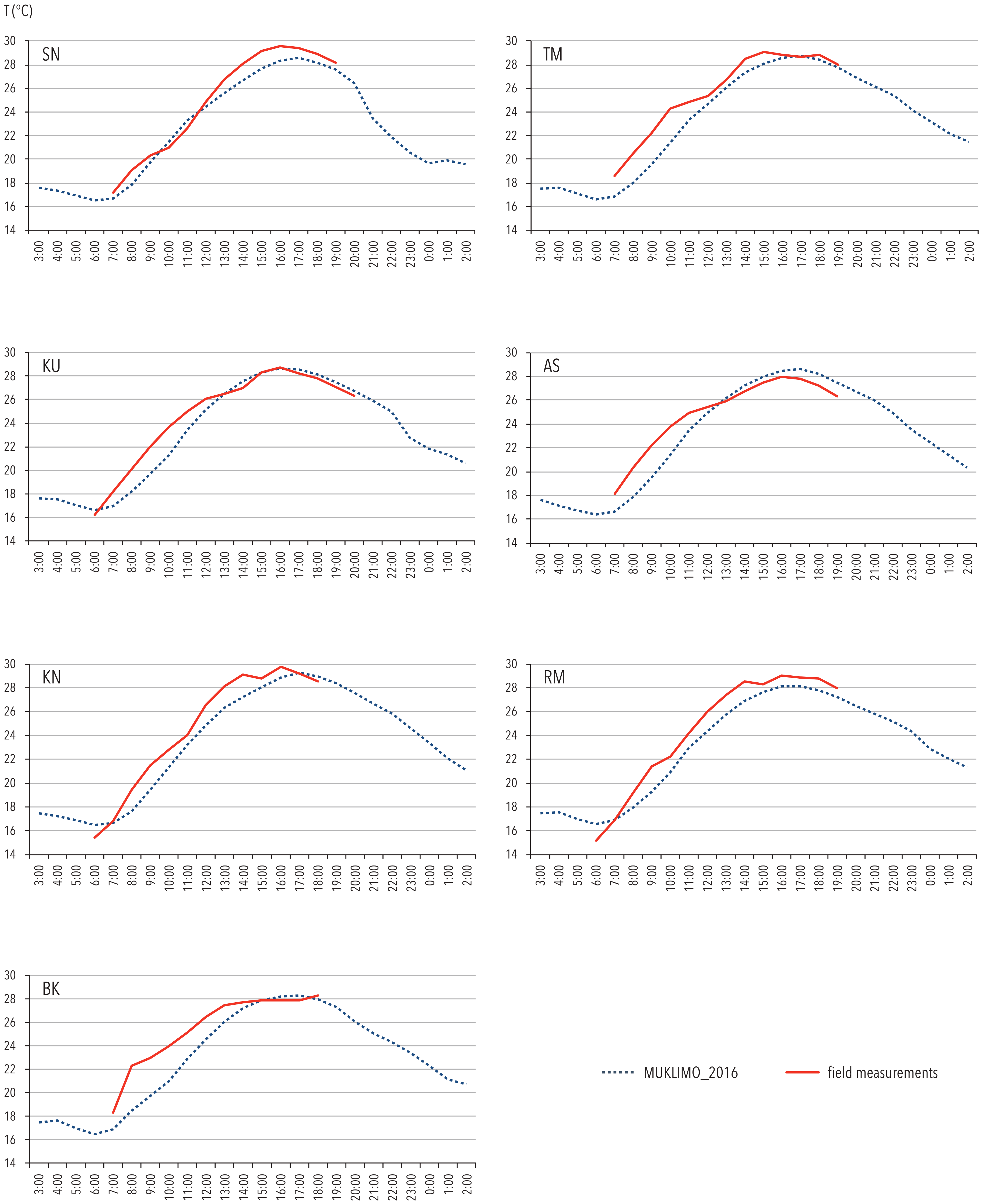

Fig. 9 (continued) – Comparison of modelled temperatures and real measurements in 13 sample points in the FUA Bratislava for modelled day, 11 June 2015.

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