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CHARACTERISTICS OF WINTER URBAN HEAT ISLAND IN BUDAPEST AT LOCAL AND MICRO SCALE

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Abstract

Most of the urban heat island (UHI) researches focused on the phenomenon in summer. They mainly studied the causes, different functional areas, and possible mitigation measures to reduce the high temperature in urban areas. However, UHI also exists in winter, but there are a limited number of studies on winter UHI. The characteristics and causes of UHI in winter have not been received much attention or consideration yet. This study aims to characterize the UHI feature in winter in Budapest, Hungary, based on the analysis of land surface temperature (LST) in relation to the factors of elevation, slope exposure, residential type, and snow coverage. Five different Landsat images in the winter season were applied to detect the surface temperature; besides, pictures of the thermal camera at a micro-scale were also used. Results showed that UHI intensity was not strong in winter; built-up areas were warmer than other urban areas. Topography was one of the significant factors affecting the surface temperature in winter. The surface temperature of the hills (300 m asl) was lower than that of the lowlands (below 120 m asl). The south-facing slopes and south oriented buildings were warmer than north-facing slopes and buildings oriented to the north. Areas with snow coverage had a lower temperature than no snow coverage areas. These findings could give general guidance for further UHI research, urban planning as well as landscape design.

Keywords: UHI, Surface temperature, LST, Topography, Slopes, Aspects, Snow, Influencing factor

INTRODUCTION

Urban heat island (UHI) is a phenomenon that is recognized as the temperature is higher in highly urbanized areas than its surroundings (Oke, 1973, 1982, 1987). This kind of local temperature difference had caused serious environmental problems worldwide. Increased energy consumption, modified natural habitats, endangered human health and well-being are the symptoms of urban heat island (UHI). This phenomenon was first discovered and proposed by Luke Howard in 1818 (Howard, 1818). He analyzed the records of temperature in London and recognized the special effect of urban areas on the local climate. Today we are aware of the general urban heat island effects in summer all over the World. The heat island can be measured by land surface temperature and by air temperature as well (Deilami et al., 2018). The land surface temperature (LST) is the main approach to map the UHI phenomenon based on satellite images covering large areas on a regional scale. Air temperature is measured by weather stations collecting data of exact predefined locations. At the same time, connections between surface and air temperature are also a research concentration.

Most studies on UHI were focused on the summer (Kolokotroni and Giridharan, 2008; Middel et al., 2012; Zhang et al., 2017a; Lam and Lau, 2018;) because this UHI effect is significant during the hot season, the radiation of the solar energy makes the surface stored more heat during the daytime. Thus studies showed that surface urban heat island (SUHI) is related to the surface albedo and heat transfer by the coverage materials (Bhattacharya et al., 2009; Erell et al., 2014). For instance, impervious surfaces such as roads and concrete surfaces absorb more heat than green spaces and water areas. During the night, the buildings and other impervious surfaces in the urban areas release the heat stored at daytime (US EPA, 2014; Zhang et al., 2017b), as a consequence, making the UHI intensity larger than in the day. Studies also investigated the impact factors related to UHI effects, such as urbanization (Chapman et al., 2017; Mathew et al., 2017), urban form (Li et al., 2012), landscape structure (Li et al., 2011), impervious surfaces percentage (Henits et al., 2017), green space coverage (Oliveira et al., 2011; Kong et al., 2014), water surface and geography factors (Mathew et al., 2017; Cai et al., 2018), but most of the research chose the period in the summer season. With the development of satellite image processing, the winter season UHI could be documented as well. However, there are a limited number of articles dealing with the winter UHI and related effects.

For the effect of NDVI and surface temperature in wintertime, a study showed that lower temperature was observed in the high vegetated area at daytime in Tokyo's urban areas in 1990. Based on NDVI analysis, densely vegetated areas have lower temperatures in winter in the urban areas at night. On the contrary, the densely vegetated areas appeared with higher temperatures in the suburban areas in the same conditions. The relationship between vegetation and temperature was not significant in the urban area at day time, but the high vegetated area tends to lower temperature in suburban areas (Kawashima, 1990). In further research, Kawashima et al. (2000) employed the Automated Meteorological Data Acquisition System (AMeDAS) to obtain air temperature in winter. His research group found that the value of NDVI has a sensitive relationship, but no regulation with the air temperature by linear regression analysis, and they also found surface temperature can explain 80% of the observed variation in air temperature. The urban heat island exists in summer and winter (Zhang and He, 2007; Mathew et al., 2017). The distribution of land surface temperature (LST) is also in relation to the city structure. The studies showed that the variation in the wintertime is less strong compared with other seasons. However, land cover types and LST distribution have a stronger relationship in all seasons (Liu and Weng, 2008). In London, the winter UHI investigation indicated that most outdoor temperature changes are dominantly caused by climate factors (like wind velocity, sky condition) and not the on-site variables (Giridharan and Kolokotroni, 2009). A similar result appeared in Shanghai (China): UHI intensity was relatively weak during the winter period compared to summer and springtime during 1997 and 2008 (Li et al., 2012).

In the wintertime, snow is one of the significant factors which affect LST. The high albedo of snow changes the surface radiation balance; its low thermal diffusivity insulates the local climate (Hinkel et al., 2003; Westermann et al., 2012; Lokoshchenko, 2014). Previous research showed that the snow cover area correlated with surface brightness temperature in California, USA (Yin and Zhang, 2014). When the local surface was covered by snow, the snow area could increase rapidly in snowy weather. The brightness temperature was a good indication of the presence of snow. However, the study revealed that when the snow was more than 0.5 m deep, or the snow was beginning to melt, the brightness temperature had less useful information for LST.

Another investigation demonstrated the existence of UHI in Barrow, Alaska (USA). It used soil and air temperature from the temperature records, and the peak UHI magnitude (UHIM) appeared in the late evening and the early morning. The average temperature in the urban area was 2.2 °C warmer than the hinterland. UHI magnitude generally increased with decreasing air temperature in winter, reflecting anthropogenic heat's input to maintain interior building temperatures (Hinkel et al., 2003). However, in wintertime, urban heat island gave an effect on species migration more extended in Central Europe (Sachanowicz et al., 2018). The growing detection of bat species' winter occurrence (Pipistrellus nathusii, Chiropter asp.) has coincided with an increase in mean winter temperatures and urban warming. Recently recorded new wintering areas for these species, mainly in Central European cities, have largely extended its wintering distribution to the northeast due to the winter urban heat island effect. The orientation of buildings on the streets raised some design challenges, especially considering solar and wind directions (Erell et al., 2014). The building orientation to the sun affects the amount of solar radiation absorbed. A Greek study found that streets on the east-west axis were less exposed to solar radiation (Andreou, 2014). So it could be interesting to do further step on the orientation and aspect field impact on the surface temperature at the city level.

According to the UHI studies made in Hungary, the strongest UHI intensity occurs in the urban center during the heating season. This phenomenon was not dependent on heating, but the season and weather characteristics (Unger and Makra, 2007). Winter UHI existed because of the heating and different surface materials of buildings, and the materials of buildings have low heat capacity. The water surface was warmer than other land cover types in winter (Oláh, 2012). Budapest downtown's annual mean temperature was 1.2 °C higher than outside the city, and the peak month was in January (Probáld, 2014). Due to the meteorological conditions in winter (except February) and autumn, the UHI phenomenon appeared less intensive than that of summer and spring in Debrecen (Hungary) based on long-term data (László et al., 2016). The analysis of the relationship between the SUHI intensity and the Local Climate Zone (LCZ) classes for the Budapest study showed that the SUHI intensity variability was generally greater in summer than in winter, which was caused by the difference in solar radiation in these two different seasons (Dian et al., 2020).

From UHI literature reviews, we found that most studies focused on UHI during summertime, as this is when temperature differences are clear and can be easily understood. It can be quantified by surface and air measurements but surveys in winter season UHI are not so current and widespread. This paper intends to characterize the surface urban heat island phenomenon in Budapest in the winter season, from the city scale to the local scale. Some part of our research was based on satellite images, similar to previous research about summer urban heat island in Budapest (Gábor and Jombach, 2009). We used satellite images and thermal camera surveys to illustrate surface temperature maps and visualize the on-site surface temperature in different site locations.

This study aims to analyze the characteristics of the land surface temperature (LST) of Budapest in winter. The general goal was to discover winter heat island characteristics of Hungary's capital city based on surface temperature analysis by satellite images and field surveys. Our study mainly focused on the following questions:

1) What are the general winter urban heat island (UHI) characteristics?
2) How do elevation, slope aspect and building orientation modify surface temperature?
3) How does snow cover modify the land surface temperature (LST) of Budapest?

STUDY AREA

Budapest is the capital city of Hungary, located in the central part of the country. The city had an estimated population of 1.75 M inhabitants and has a land area of about 525 km^2. Budapest's climate is moderately continental based on Köppen-Geiger climate classification, which has relatively cold winters and warm summers (Beck et al., 2018). According to the long-term observation data record from 1991-2019 (OMSZ, 2020), the mean temperature in Budapest is 11.3 ℃. The warmest month (with the highest average high temperature) is July (26.7°C). The month with the lowest average high temperature is January (2.9°C).

METHODS AND MATERIALS

Digital satellite images, thermal camera images, and an elevation model were used. The key methods were land surface temperature calculation with a combination of field surveys, GIS analysis, and statistical analysis. The measured temperature data is mainly LST from satellite imagery. Additionally, we used a digital elevation model to analyze the slopes and aspects to explore different temperature characteristics based on topography. GIS software is used to retrieve the surface temperature from Landsat 8 satellite images. The sample sites of different land-use types were selected based on Google's very high resolution (VHR) satellite image and field survey experience. Zonal statistical tools summarized temperature. At the same time, Excel statistical tools were used to analyze and show the outcomes. Field photography and thermal images were also applied to illustrate the results.

Satellite data resource

In this study, five Landsat 8 satellite images were used (Table 1). These were chosen and downloaded from the USGS (https://earthexplorer.usgs.gov/). The images focus on the peak winter from November to March. Budapest's heating season is mostly from mid of October to mid of April, and this period is represented by leafless landscape scenery. The images were prepared on sunny days around 10:33 (Central European Time) and these have almost no cloud coverage, which means that the results will show the typical situation of bright, sunny winter days. The only image with partial snow coverage (06.01.2017) was used for snow cover effect analysis.

Retrieval of land surface temperature

The land surface temperature was calculated by GIS-related software from Landsat 8 satellite images. In this study, QGIS and ArcGIS software was used to calculate LST values. The process mainly includes five steps from the satellite image to the LST map based on the radiative transfer equation (RTE) method (Li et al., 2020).

1) Conversion to "Top of atmosphere Radiance"
2) Conversion to "Top of Atmosphere Brightness Temperature"
3) Calculation of "Proportion of Vegetation"
4) Calculation of "Land Surface Emissivity" (LSE)
5) Retrieval "Land Surface Temperature" (LST).

For the analysis, we used single land surface temperature maps (based on all images of Table 1) and Budapest's average LST map.

Digital elevation model

To analyze topographic characteristics and define the significant southern and northern slopes, we used the SRTM digital elevation model. The model was downloaded from the website of USGS. The spatial resolution is 30 m. For the temperature analysis related to the elevation, we identified areas above 300 m asl as "hills," while the areas below 120 m were identified as "lowlands". For the slope analysis based on the SRTM model, we selected slopes steeper than 10%. Based on aspect analysis, we could select the south-facing slopes and the north-facing slopes separately. The sample sites were the largest 27 contiguous areas; each of them was larger than 5.0 hectares.

Thermal camera imaging

We used thermal imaging to illustrate surface temperature in the city and the instrument was the "Seek thermal Pro" camera with a 320 x 240 resolution thermal sensor. It is portable, lightweight, and easy-to-use, based on the Seek application on a smartphone. The method included a parallel use of real photography in the field. An illustration can be shown by comparing thermal and real images (Fig. 1)

Table.1 Landsat images used to estimate land surface temperature

Date	Satellite types	Scale
27.11.2013	Landsat 8 OLI-TIRS	Full Budapest coverage
15.02.2014	Landsat 8 OLI-TIRS	Full Budapest coverage
18.02.2015	Landsat 8 OLI-TIRS	Full Budapest coverage
06.01.2017 *	Landsat 8 OLI-TIRS	Full Budapest coverage
25.01.2018	Landsat 8 OLI-TIRS	Full Budapest coverage

*The satellite image was only used for snow-cover analysis

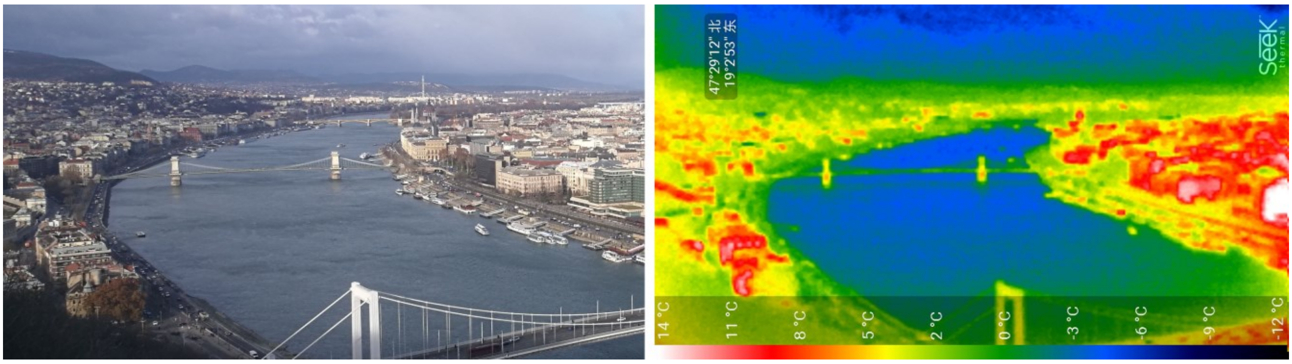

Fig. 1 The real image and the thermal image showing the Budapest city center's surface temperature measured by the Seek Pro heat camera from Gellért hill (at 12:50 on 28. 12. 2018). The thermal image and the real image were prepared simultaneously so that the areas of different temperatures could be recognized. The thermal image includes the legend of temperature in Celsius degree. A diverse colour scale can be set with the software. The analysis of thermal images in the article was assisted by the combined use of real photo contours.

Statistical analysis

The zonal statistical analysis was applied to get the mean LST values from the map (Chen et al., 2006). By using this tool, a mean LST was extracted from all corresponding pixels. According to a previous study (Woodcock and Strahler, 1987), the optimal spatial resolution to capture spatial patterns using remotely sensed imagery was approximately half to three-quarters of the object dimension's size in the scene. A previous study showed that 60×60 m spatial resolution is approximately the optimal spatial resolution in analyzing the scale effect on monitoring UHI (Chen et al., 2006). Therefore, we performed analyses at the finest spatial scale as the data allowed, which was appropriate to capture UHI's spatial features and relevant land-use types. The sample sites we selected were all bigger than 5 hectares; this means that they were much higher above the limit that previous research.

RESULTS AND DISCUSSION

Our results are grouped and discussed according to the general goal and the questions we aimed to answer. Thus we interpreted the results of Budapest in general and for its districts. Then we analyzed the influence of topography and snow coverage on temperature changes.

General winter UHI characteristics in Budapest

We prepared five separate land surface temperature maps (based on the images in Table 1.) and an LST average map for Budapest (Fig.2) representing the whole city region. From this winter average LST map (Fig. 2) the following general outcomes we listed:
The urban heat island existed in Budapest in the analyzed winter days. The winter LST map demonstrated that the temperature was decreasing from urban centers to non-urbanized areas. Although the differences were not significant, the temperature in wintertime was generally low. According to the average map, it varied between -2.7℃ and 7.6℃.

Buda side was generally colder than the Pest side. The western forested and hilly parts in Buda were cooler than the densely urbanized Pest side. We compared the mean LST of different districts in Budapest (Fig. 3a). The 23 districts of the city had a surface temperature above 0.0 ºC. The XII district was the coldest, being 1.1 ℃ on average. The warmest districts were the VII and IX districts, which indicated up to 3.3 ℃ (Fig. 3b). The LST's spatial characteristics reflect that the warmer districts were located in the densely built-up central and south-eastern areas and airport area, while the colder ones are closer to the "semi-natural" areas (i.e., forests, hills) at west.

Warmer spots were mostly dispersed within build-up areas. Spatial distribution of surface temperature based on field thermal photo from aerial photography on Fig. 1, showed similarly that the temperature in built-up area patches was the highest, sometimes reaching peaks like 14℃ in the high resolution. The city's warmest elements were the airport, logistical buildings, huge store and parking areas, garages, and railway stations, which had generally valued above 5 ℃ on average. The urban parks, forests, and other woodland areas were usually colder than the city's average temperature. The Densely built-up residential areas downtown had a higher surface temperature than the suburban-style family house dominant garden cities.

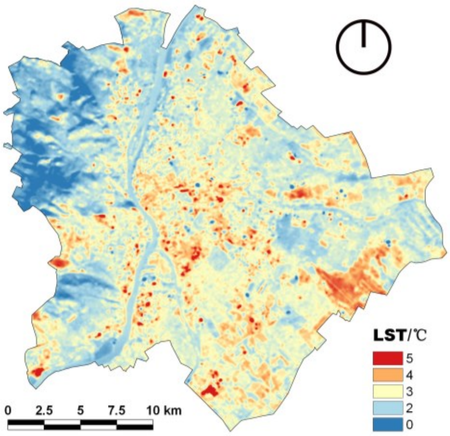

Fig. 2 The average winter land surface temperature (LST) map (based on five images in years 2013-2018) in Budapest

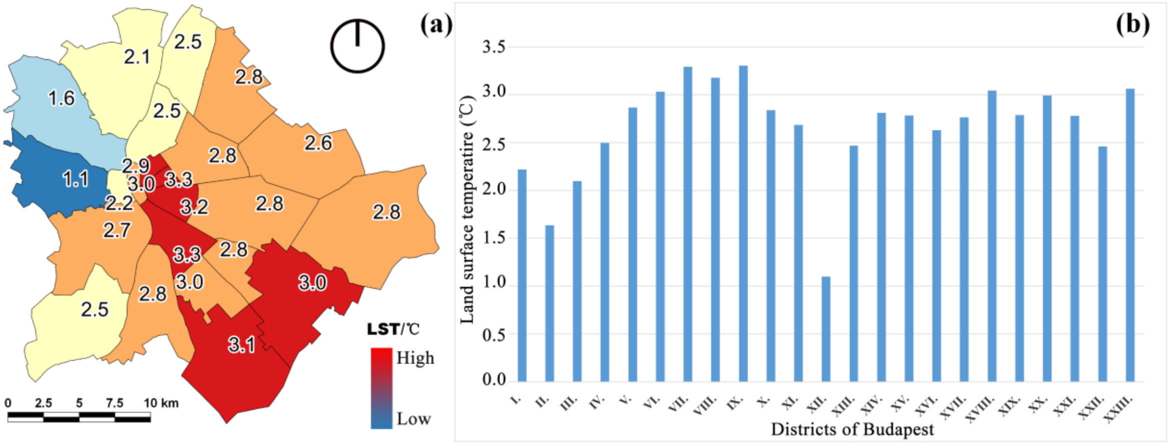

Fig. 3 The mean land surface temperature (LST) map of the 23 districts in Budapest (a) and the temperature differences between the districts (b).

The topographic differences seemed to influence LST depending on the aspect of slopes and sun angle. This phenomenon, we decided to analyze in detail in some selected sampling areas.

Elevation and aspect influence on LST

Based on the SRTM digital elevation data, we analyzed how the elevation and aspect influence the land surface temperature (Fig. 4a). By comparing the average surface temperature of the two elevation classes (above 300 m asl and bellow 120 m asl), it could be seen that the higher the altitude, the lower the surface temperature is. It could be concluded in the topographical division of Budapest that the surface temperature in the lowland was higher. The difference between the two elevation classes was 2.06 °C on average (Fig. 4b). The single image analysis showed that the lowest temperatures could be detected in the hills (below -4 °C) while the highest was in the lowlands (sometimes above 10 °C). In summary, our results showed that hills were more than 2.0 °C colder than the lowlands in Budapest.

The surface temperature is directly related to the sunlight, the absorption, and the heat storage capacity of the surface. Therefore, the slope orientation (exposure) will inevitably affect the distribution of surface temperature. Comparing the aspect data extracted from the SRTM digital elevation model can be seen in Fig. 5. The temperature in the southern slope surface is every case higher than any slope on the north side. In Sas hill and Gellért hill, the northern slope was around 1 °C, and the south slopes were around 4 °C on average. The temperature difference, on average, was 2,7 °C. We could sentence that the southern slopes of hills were more than 2 °C higher than the northern slopes. The high-resolution field survey with the thermal camera made the phenomenon even more obvious as the extreme temperatures of different slope aspects and building orientations show this in more detail (Fig. 6 and 7). Concluding the results of satellite image analysis and thermal image analysis, it could be stated that during the winter season, a special kind of heat island could be determined in Budapest due to low sun angle. This kind of vertical factor on UHI can be called the "vertical heat island". The sun's vertical elements are illuminated by the sun mostly from the side, so the heat island shows up by slopes, walls, facades significantly, which means that it can be measured better from the field than from the air. Therefore, it is also recommended to have field surveys with thermal camera applications.

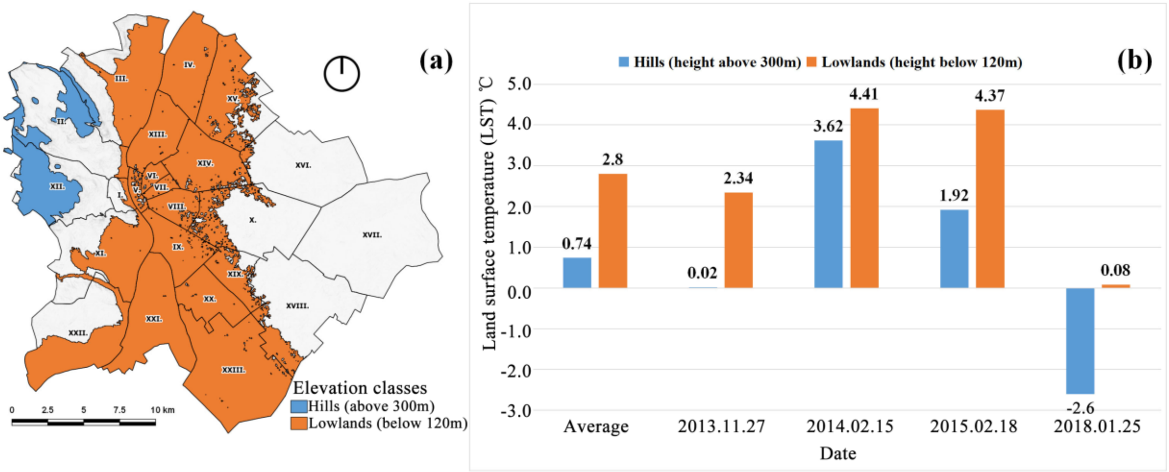

Fig. 4 Mean land surface temperature (LST) of hills and lowlands (a) in Budapest and comparison histogram (b).

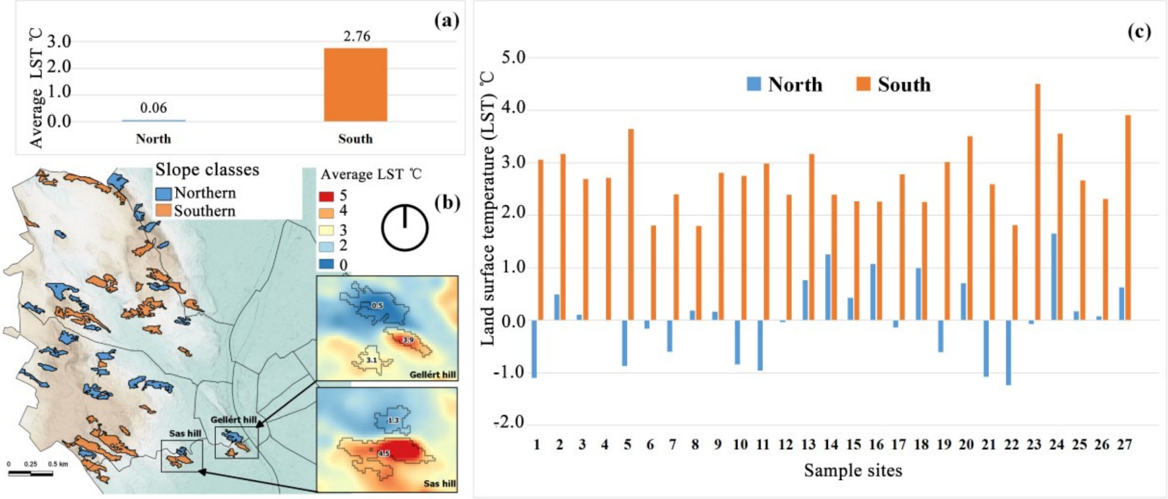

Fig. 5 LST of the two exposure types (a), spatial distribution of selected sites (b) and the average LST of sample sites (c)

The Buda Castle complex showed that the groups of buildings facing different directions could result in a temperature difference of 10 °C.

Relationship between LST and snow cover

To analyze snow cover's cooling effect, we selected a particular image of the year 2017 that had partial snow coverage. This image had snow cover in the southeast and no snow cover on the northwest (taken at 10:33 on 06. 01. 2017). Fig. 8a clearly shows the boundary that divided the city into two parts: areas with snow-cover and without snow-cover. We compared the differences between these two parts. The LST map in Fig. 8b shows that the snow-covered area's surface temperature was lower than those without snow cover. These could lead to similar conclusions like other previous studies (Hinkel et al., 2003; Westermann et al., 2012; Lokoshchenko, 2014). Due to the high albedo of the snow surface, those areas had less heat absorption and storage.

To further explore the influence of snow cover on the surface temperature, we selected sample sites to comparison of the different land-use types. We selected 40 sites representing the two most frequent land-use types of the northeastern suburban area of the XV., XVI., and XVII. Districts (Fig.9):

- Garden community (a type of residential area, dominated by family houses and gardens),
- Arable land (plowland mostly with no vegetation in winter, bare soil)

We selected ten snow-covered sites within the residential areas with gardens and another ten sites without snow coverage. Each site was bigger than 5 hectares but smaller than 20 hectares. Our results show that the snow-covered garden community blocks' temperature was lower than the no-snow covered areas (Fig. 10), as the average temperature difference was 2.66 °C on the given day.

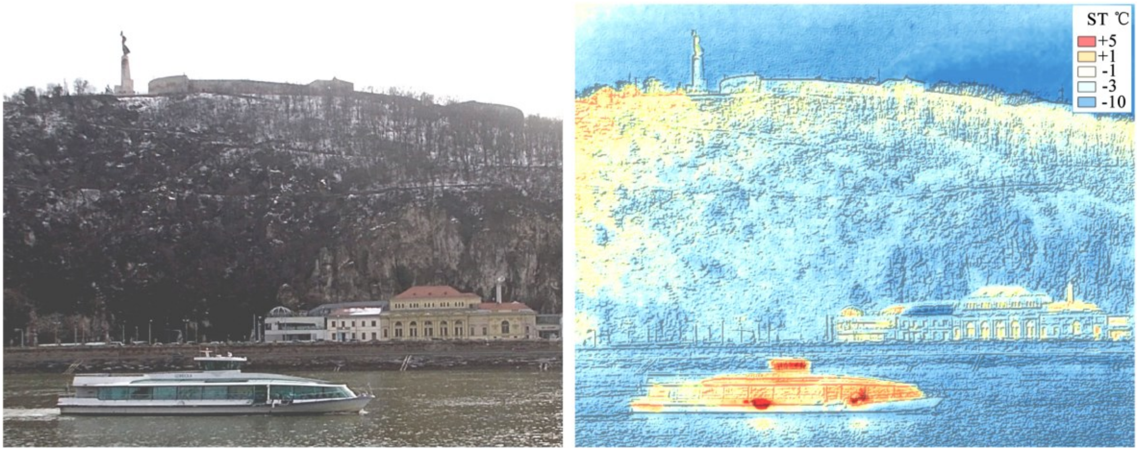

Fig. 6 The northern slopes of Gellért hill were, in some cases, 10 °C colder than the southern slopes on high-resolution thermal camera image (taken at 14:20 on 13. 01. 2019.).

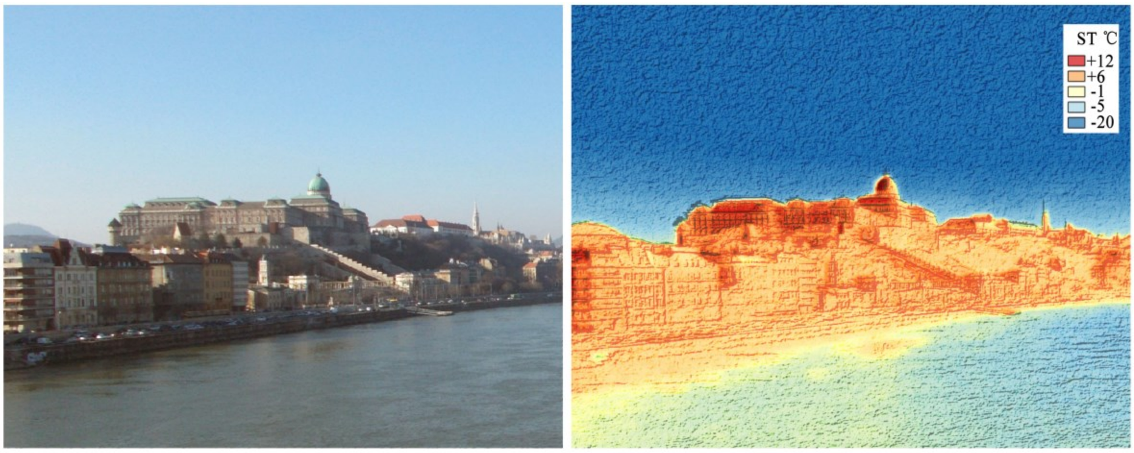

Fig. 7 Surface temperature (ST) of southeast slopes in Buda Castle hill. The castle walls facing south have significantly higher values than the walls facing east (taken at 14:09 on 07. 02. 2019.).

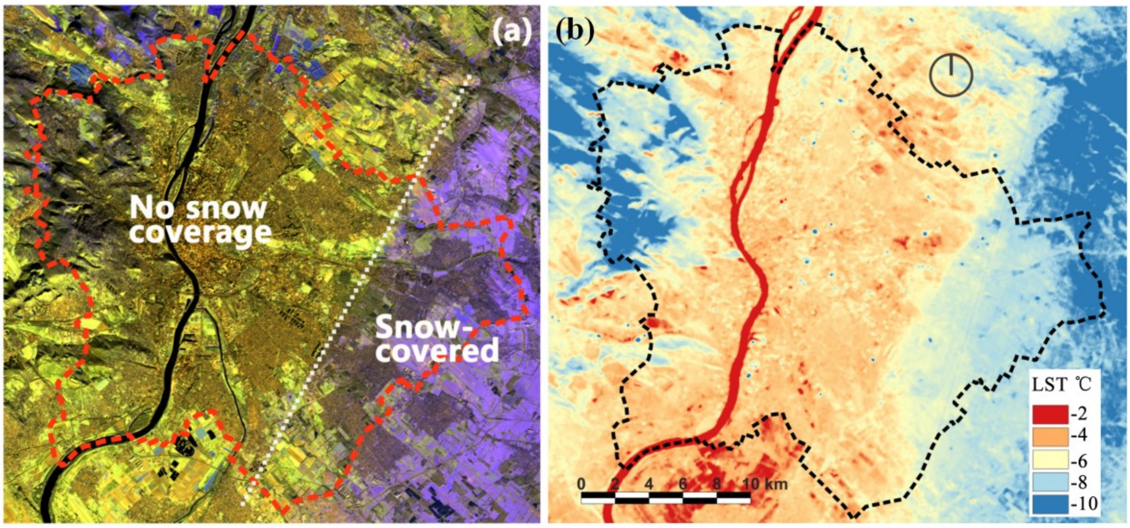

Fig. 8 The Land surface temperature (LST) of the snow-covered area and no snow coverage on 06. 01. 2017 (taken at 10:33). False color images based on the Landsat 8 image (a) and LST map (b).

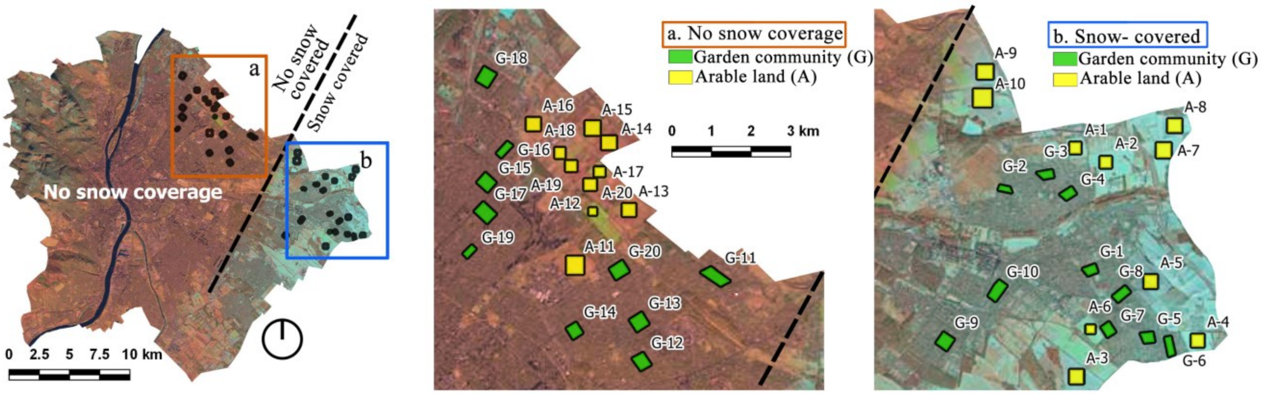

Fig. 9 Sample sites of garden community and arable land in the outer districts of Budapest. The selected 40 sites represent the most frequent land use types in the region.

The results for arable land showed that the snow-covered ten sites had lower temperatures than the areas of no snow cover (Fig. 10). The average temperature difference reached 4.36 ℃.

The results showed that snow cover could reduce LST by several degrees, but there was a slight difference in the intensity of the decrease in the two land-use types. Our study, based on 40 sample sites, showed that the arable land could be slightly colder than the garden community with snow coverage. Snow could cool down LST in arable land more significant than in the garden community. The snow had a less cooling effect in the garden community than in arable lands, probably thanks to the human activity and variety of artificial elements in the built-up area. This fact reinforced the results that in Budapest, a moderate version of UHI exists in winter and affects snow cover.

The high-resolution thermal images of field surveys confirm the satellite LST results. From Fig.11, we can see that the surface temperature of the snow-covered area is significantly (5 ℃) lower than the no snow-covered surface. The top of the pavilion is at the same angle as the top of the trash can, but the top of the trash bin was not covered by snow; due to different materials and larger surfaces, the pavilion preserves low temperature.

The exemplary thermal image shows similar effects along Szilas creek. The creek slopes were not covered by snow and were 5°C warmer than the snow-covered parts Figure 12 Compared to grassy slopes, the snow has higher reflectivity and lower heat capacity, resulting in less heat storage; therefore, indicating lower temperature.

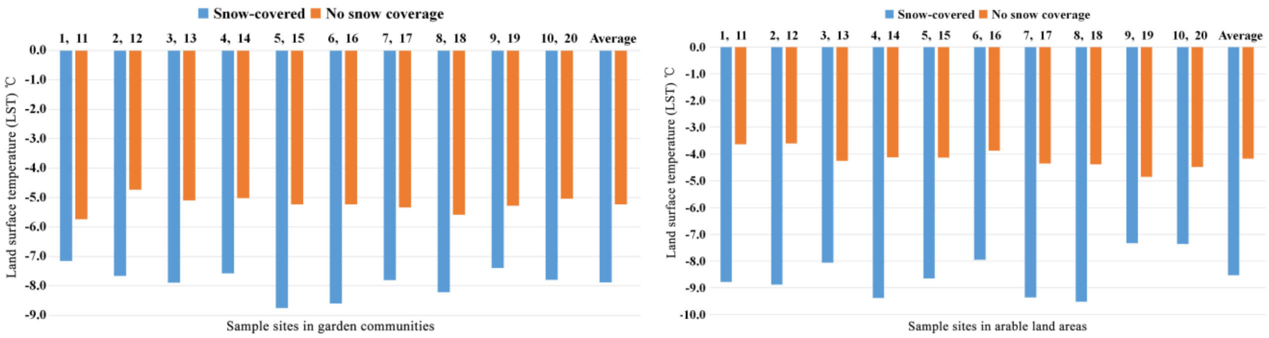

Fig. 10 Comparison between snow-covered and no snow-covered sites in residential areas with gardens (garden community) (left) and in arable land (right).

Fig. 11 Surface temperature (ST) differences indicated by snow cover in Hermina Sport and Leisure Park (XVI. District) (taken at 13:32 on 12.01. 2019).

Fig. 12 Surface temperature (ST) differences in a patchy snow-covered side Szilas creek (XVI. District) (taken at 13:59 on 12.01. 2019).

CONCLUSIONS

The study based on surface temperature analysis indicated that winter urban heat island exists in Budapest. Although the difference between the lowest and highest temperatures was not great, the study still revealed that the urban area was warmer than its surroundings. Warmer spots were mostly dispersed within built-up areas. The city's warmest elements were the airport, logistical buildings, huge store and parking areas, garages, and railway stations. Nevertheless, the parks, forests, and other woodland areas were colder than the average temperature. In addition, downtown densely built-up residential areas had a higher surface temperature than the suburban-style family house dominant garden communities. In general, it was revealed that the hilly Buda side (western) was colder than the low-lying and flat Pest side (eastern). The comparison of Budapest's 23 districts revealed that the inner districts (VII, IX) were the warmest, and the XII district was the coldest.

Topography was a significant factor influencing the surface temperature in winter. Our research showed that the surface temperature of the hills (300 m asl) was lower than that of the lowlands (below 120 m asl). The average temperature difference reached 2.68 ℃. The slope also influenced the land surface temperature (LST). The results showed that south-facing slopes and south oriented buildings which absorbed solar heat for a long time were warmer than north-facing slopes and buildings oriented to the north. The results were especially spectacular in case Sas hill, Gellért hill, and buildings of Buda Castle. As a result of the low sun angle, a special kind of heat island, the "Vertical Heat Island," could be identified. The landscapes' vertical elements were illuminated and warmed up by the sun mostly from the side, so the heat island developed, especially on hill-slopes, walls, and facades of huge buildings.

Areas with snow coverage had low temperatures. Based on the result of the land surface temperature (LST) map of 06. 01. 2017 the comparison of snow-covered garden communities and arable lands proved, the areas without snow cover were lower by 2-4 ℃ than areas with snow cover. The same phenomenon appeared on high-resolution thermal images. Based on 40 sites, our study showed that snow has a less cooling effect in garden communities than on arable lands. This fact reinforced the results that in Budapest, a moderate version of urban heat island exists in winter and affects snow cover.

Based on the results, we give the following general guidance for further research and proposals for planning and design:

- Urban heat island characteristics of winter and summer should be compared in future research. Some elements show that the summer's advantage is winter's disadvantage. This can be influenced by coloring, choice of built or plant material, shading by built structures or trees.
- We recommend that planners in Budapest avoid the introduction of evergreen trees as shading elements near the southern side of buildings, as they provide a cooling effect in winter and block sunshine.
- We recommend to minimize winter heating costs; the new residential areas should consider the orientation of buildings with more attention to the south direction.

The paper collected characteristics of winter urban heat island in Budapest, mostly defined by natural and land-use dependant factors. The heat island is locally increased with individual human activities (traffic, transport, heating, production, etc.). These human activities influenced factors that need further research in the future.

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