ASSESSING LAND SURFACE TEMPERATURE IN URBAN AREAS USING OPEN-SOURCE GEOSPATIAL TOOLS

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ABSTRACT:

Land surface temperature (LST) in urban areas can be traditionally observed by thermal remote sensors. The increasing availability of 3D city models provides an alternative approach based on geospatial modeling. Using solar radiation tools and scripting in GRASS GIS, we have developed a physically-based LST model that can be used to estimate LST in urban areas represented by vector 3D city models. It uses standard input parameters such as solar irradiance, albedo or convection heat transfer coefficient for urban surfaces. The solar irradiance is estimated using the v.sun solar radiation add-on module in GRASS GIS. The LST values are calculated using map algebra operations using a Python script. The suggested methodology was applied to the study area in the city of Košice, Slovakia. Results indicate that urban morphology has a strong impact on spatial distribution of LST during the daylight hours. The accurate parameterization of urban surfaces can increase the accuracy of the model that can be used for urban planning, optimization of energy use in buildings or mitigation of urban heat island effects.

1. INTRODUCTION

Land surface temperature (LST) in urban areas is an important indicator of the urban heat island (UHI) phenomenon. LST is affected by various factors such as solar irradiance, cloudiness, wind or urban morphology (Voogt and Oke, 1997). Traditionally, LST is observed and recorded by thermal remote sensors. For example, thermal satellite sensors are very popular for assessing the UHI effect on a global scale such as MODIS, Sentinel 3, ASTER, Landsat 7 ETM+, or Landsat 8 TIRS. However, these sensors provide rather low spatial (60 m to 1000 m) and temporal resolutions (several hours to days) of satellite observations that limit the accurate estimation of LST in urban areas for local studies and specific time periods (Tooke et al., 2012; Hu and Wendel, 2019). Airborne or terrestrial remote sensing can be viewed as another option for capturing higher spatial resolution of thermal data but it is not feasible to be used for large urban areas with increased periodicity. However, the increasing availability of the high-resolution geospatial data and adequate modeling techniques provide an alternative approach to high-resolution estimation of LST in urban areas.

Several studies showed the potential of geographic information system (GIS) tools, digital surface models (DSMs) and 3-D city models for the estimation of solar radiation in urban areas (e.g., Hofierka and Kaňuk, 2009; Hofierka and Zlocha, 2012; Redweik et al., 2013; Freitas et al., 2015; Biljecki et al., 2015). Solar irradiance is a key factor affecting LST during daylight periods, especially under clear-sky situations. Nevertheless, LST assessment requires a physical model combining surface-atmosphere interactions and energy fluxes between the atmosphere and the ground. Properties of urban materials, in particular, solar reflectance, thermal emissivity, and heat capacity influence the LST and subsequently the development of UHI, as they determine how the Sun's radiation energy is reflected, emitted, and absorbed (Hofierka et al., 2020b; Kolečanský et al., 2021). It is clear, that the problem complexity requires a comprehensive GIS-based approach.

Recently, open-source solar radiation tools implemented in GRASS GIS has been successfully applied to various environmental and solar energy resource problems (Hofierka and Kaňuk, 2009). For example, the r.sun solar radiation module provides a spatially distributed assessment of solar radiation for any time horizon or period. As shown by Hofierka et al. (2020b), these calculations can be efficiently used in estimation of LST assuming the absorbed solar radiation is directly converted to LST using the Stefan-Boltzmann Law. This solution also requires a DSM representing a land surface morphology, spatially distributed data representing thermal properties of land surfaces and concrete meteorological conditions (Hofierka et al., 2020a, 2020b; Kolečanský et al., 2021). This LST model is implemented in GRASS GIS as a LST module written using a script (shellscript, Python). Using this script, the r.sun solar radiation model in GRASS GIS is used to calculate the effective solar irradiance for selected time horizons during the day. The solar irradiance calculation can account for an attenuation of beam solar irradiance by clouds estimated by field measurements (Hofierka et al., 2020a). The proposed LST model also accounts for a heat storage in urban structures depending on their thermal properties and geometric configuration.

However, this LST model is for 2D surfaces only. Urban areas with vertical surfaces such as facades are only approximated by a DSM. As shown by Kolečanský et al.. (2021), the estimates of solar radiation in urban areas by this approximation often leads to a substantial errors. Consequently, this may also affect LST estimates. The alternative approach is to use a vector-based 3D city model and adequate 3D geospatial tools. For example, the v.sun solar radiation module has been developed as an add-on module for GRASS GIS (Hofierka and Zlocha, 2012). It is based on the same solar methodology as the r.sun module, however, for 3D city models in a vector format. The aim of this study is to present a 3D LST model for vector-based 3D city models using geospatial tools in GRASS GIS.

2. METHODS AND DATA

2.1 The Land Surface Temperature Modeling

Typically, urban areas exhibit fluctuating thermal patterns depending on various thermal properties of the urban surface and the geometry of the urban fabric. For insolated surfaces, the equilibrium surface temperature T_S is obtained from the heat balance equation based on the Stefan-Boltzmann Law, which describes the total power radiated from the temperature of the object (Bretz et al., 1998; Hofierka et al., 2020b):

$$(1-\alpha)I = \varepsilon\sigma\left(T_s^4 - T_{sky}^4\right) + h_c\left(T_s - T_a\right), \qquad (1)$$

where α is a unitless value that represents solar reflectivity of the surface, i.e., albedo, that varies from 0 to 1, I is the total (global) solar irradiance incident on the surface ($W.m^{-2}$), ε is a unitless value that expresses the emissivity of a given surface, σ represents the Stefan-Boltzmann constant (5.6685 × 10-8 $W\ m^{-2}\ K^{-4}$), T_S is the surface temperature in equilibrium (K), T_{sky} is the effective radiation temperature, h_c is the convection heat transfer coefficient ($W.m^{-2}.K^{-1}$) and T_a is the air temperature (K).

This equation can be solved numerically, for example, by Newton's iteration method (Hofierka et al., 2020b). It should be noted that this equation disregards a heat storage in urban surfaces. The heat storage decreases the instant LST based on available solar irradiance, delays the daytime LST peak, and later, during the day, releases the accumulated heat in the evening and during the night (Hofierka et al., 2020b). Recently, this solution has been modified by Hofierka et al. (2020a) to include a heat storage factor using a hysteresis-type function suggested by Oke and Cleugh (1987). In this solution, the accumulation or release of the heat alters the effective solar irradiance I in eq. (1) with the consequence of decreasing or increasing the LST. However, the heat storage factor requires information on thermal properties of urban surfaces that often are not readily available. The estimates of LST using eq. (1) even without the heat storage factor provides a very valuable assessment of LST as demonstrated by Hofierka et al. (2020b). The calculation of eq. (1) is based on simple map algebra operations using the r.mapcalc command in GRASS GIS. In a 3D solution, the map algebra calculations are done for 3D polygons in a similar manner. The workflow for LST calculation contains the following steps: 1. calculation of solar irradiance for a selected daytime using solar radiation module, 2. calculation of eq. (1) by the Newton's iteration method using map algebra operations (the example of a script for these calculations is presented in Hofierka et al., 2020b).

2.2 The Solar Radiation Modeling in GRASS GIS

Reliable LST modeling in a GIS requires accurate estimates of solar radiation, a main driving factor affecting LST. GIS-based solar radiation models depends on digital surface models (DSMs), specific atmospheric and land cover variables derived from ground-based or satellite-based data (Hetrick et al., 1993; Dubayah and Rich, 1995; Kumar et al., 1997). These topographic solar radiation models can only be used for 2D surfaces, such as land surfaces or rooftops. However, urban areas include various vertical surfaces such as facades that cannot be adequately represented by DSMs and this leads to poor estimates of solar radiation (Kolečanský et al., 2021). The 3D city models are increasingly available for visualization and various urban applications (Biljecki et al., 2015). The v.sun radiation module for 3D city models represented by 3D vector data was developed by Hofierka and Zlocha (2012) using the same ESRA methodology (Rigollier et al., 2000; Scharmer and Greif, 2000) also used in the r.sun module and described in (Hofierka and Šúri, 2004). The v.sun solar radiation model is not a standard component of GRASS GIS, it has been implemented in GRASS GIS as an add-on module (Hofierka and Zlocha, 2012) but the module is based on the same solar radiation methodology.

In a standard distribution of GRASS GIS, the r.sun solar radiation module is available (Neteler and Mitasova, 2008) and successfully used in LST modeling using DSMs aproximating the urban morphology (Hofierka et al., 2020b). The original, clear-sky model was implemented in GRASS GIS by Hofierka (1997). The module was later extended by Šúri and Hofierka (2004) to include a diffuse component of the solar radiation and an option to calculate real-sky solar radiation. The solar methodology of the r.sun module is completely described in (Šúri and Hofierka, 2004). The module can calculate direct (beam), diffuse, and reflected solar radiation components of the total solar radiation for a specific location on land surface, day, time and atmospheric conditions under clear-sky or real-sky (cloudy) conditions. The shadowing effects of land surface features are also included in the calculations.

The r.sun module works in two modes. In the first mode, it calculates the incidence angle of solar rays (expressed in degrees) and solar irradiance values ($W.m^{-2}$) for the selected time (zonal or solar). In the second mode, the daily sum of solar irradiation is calculated for the selected day. By scripting, these two modes can be used separately or in combination to provide estimates for any desired time interval.

The v.sun module is essentially a 3D variant of the r.sun module that can also calculate beam, diffuse, and reflected solar radiation. Buildings and urban areas are represented by 3D vectors in the form of polygons. The shadowing effects of neighboring buildings can be taken into account by a vector-voxel approach dividing each considered polygon into smaller segments (Hofierka and Zlocha, 2012).

The fundamental difference between the v.sun and r.sun module is in the geometry of input data. While v.sun uses a complete or full 3D model of the city (roofs as well as vertical surfaces, such as facades), r.sun is a 2D (for a given x,y position, only one elevation value is possible). Thus, the r.sun module is more suitable for modeling the distribution of solar radiation on roofs and areas outside buildings and v.sun specifically for buildings and other artifical urban structures represented by a vector-based 3D city model.

The preparation of input data for the v.sun module is quite complicated in terms of structure and topology. The orientation of the polygons (surface normals) must be outwards, and the vertices in all polygons must be ordered in the same manner clock-wise or counterclockwise. The accuracy of the calculations depends on the size of the polygons that can be controlled by an optional parameter (Kolečanský et al., 2021; Hofierka and Zlocha, 2012).

2.3 Study Area and Data

Our study area of 4 km^2 is located in the central part of the city of Košice (48°43'35'' N, 21°15'20'' E) (Figure 1). The city of Košice is the second largest city in Slovakia with a population of approximately 240,000 inhabitants. The city of Košice is a typical example of an urban area in a temperate climate in Central Europe with warm and relatively dry summers and cold, slightly humid winters, with average daily temperatures ranging from −2 °C in January to 21 °C in July. The urban area consists of a variety of different types of buildings including commercial and residential buildings as well as roads, parking lots and urban greenery.

The 3D model of the city of Košice (Figure 2) was derived from photogrammetric and airborne laser scanning data collected by PHOTOMAP, s.r.o. company Košice. The model represents a level of detail 2 (LoD2), which means that the model contains information about the basic geometry of buildings, including roofs. The aerial survey imagery was photogrammetrically mapped in the PHOTOMOD software and the aerial laser scanning data were vectorized in the Ustation software. The 3D city model is stored in a shapefile vector format and consists of 61,766 polygons (Kolečanský et al., 2021).

Figure 1. Orthophotograph of the study area in the city of Košice.

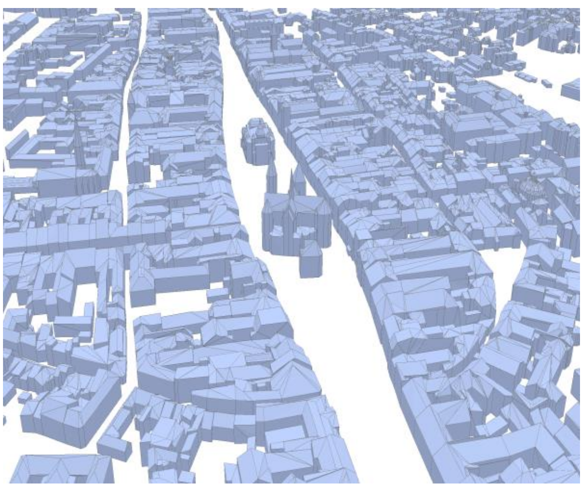

Figure 2. 3D city model of Košice.

3. RESULTS

The proposed LST methodology was applied to the 3D city model of Košice. In the first step, we calculated the total solar irradiance using the v.sun module in GRASS GIS. In the second step, we calculated LST for selected time horizons by a Python script.

3.1 Solar Irradiance

The key component of the LST model, the total solar irradiance, was calculated using the v.sun solar radiation module in GRASS GIS. The input parameters for the v.sun module included vector 3D city model with uniform albedo (0.15) and the Linke's turbidity coefficient (4.3) representing a typical city atmospheric conditions suggested by the r.sun manual page (GRASS Development Team, 2022).

The calculation was performed for 1 July, for 3 time horizons (7:00, 12:00, 17:00 local solar time) representing diurnal changes in available solar irradiance with clear-sky (no clouds) atmospheric conditions (Figure 3). The calculated total solar irradiance for 12:00 on horizontal surfaces such as flat roofs (green color in Figure 3B) corresponds well with the measured solar irradiance at the Košice airport weather station of 887.15 W.m^{-2} recorded by the Slovak Hydrological and Meteorological Institute on 30 June 2016 at 9:00 GMT (10:12 local solar time) with weather conditions close to a clear-sky situation simulated in this study.

Solar irradiances in the morning (Figure 3A) and evening (Figure 3C) show large differences between various urban surfaces caused by aspect of facades. For example, the shaded facades receive only 150-200 W.m^{-2} of total solar radiation (dark blue color in Figure 3A and Figure 3C) due to a lack of beam radiation in comparison to facades directly insolated by the Sun (700-800 W.m^{-2}). Subsequently, solar irradiance is converted to LST according to the LST model defined by eq. (1). These figures indicate that the urban morphology has a strong impact on the amount of solar radiation available during the day. Such estimates may be also crucial for solar energy applications such as photovoltaic or thermal installations.

3.2 3D Land Surface Temperature

LST was calculated using a Python version of the lst.stefan-boltzman.sh shellscript published in (Hofierka et al., 2020b). The original script was developed for 2D raster calculations and output of the r.sun solar radiation module. This Python version is for vector data, however, the physical principles are the same.

We used the following initial conditions for the LST model: the initial estimation of the land surface temperature 300 K, the effective radiant sky temperature T_{sky} = 280 K and the air temperature T_a = 290 K for 7:00, 300 K for 12:00 and 304 K for 17:00. This follows a typical summer day meteorological conditions in Košice. The convection heat transfer coefficient was uniformly set to 15 representing an averaged value typical for roofs (Hofierka et al., 2020a,b). We used 5 iterations of the Newton's algorithm to get sufficiently accurate results of LST values (T_s) from eq. (1).

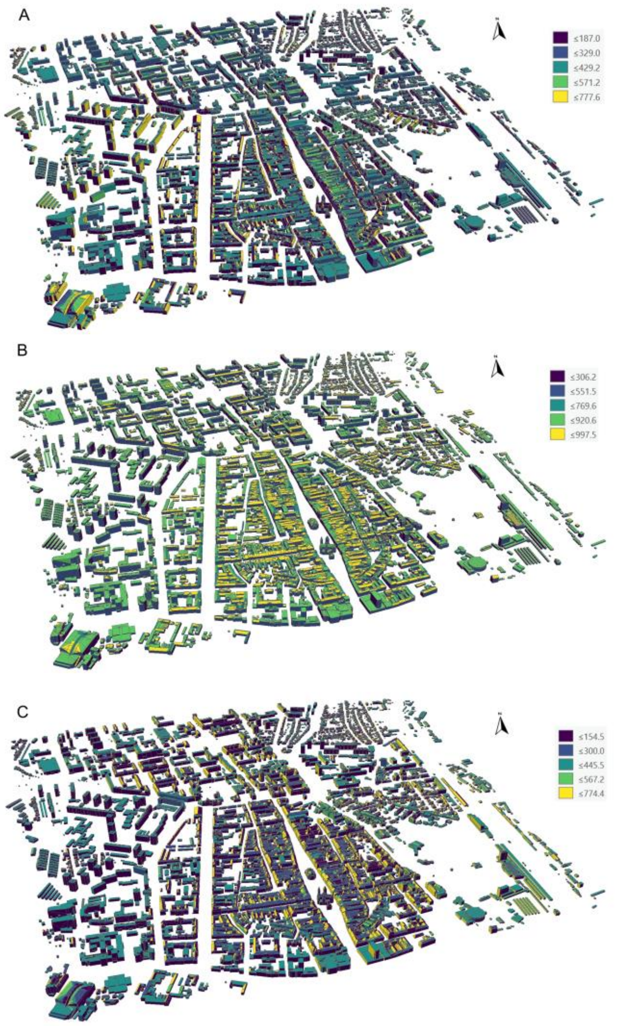

Figure 3. Solar irradiance (W.m^{-2}) calculated by the v.sun module in the city of Košice at A) 7:00, B) 12:00, C) 17:00 on 1 July.

Figure 4 shows the resulting LST for the selected time horizons. The modelled temperatures are obviously associated with total irradiances since the other parameters are spatially uniform. However, it is clear that urban morphology is a very important factor for LST. The amount of solar irradiance and LST are strongly affected by slope and aspect of surfaces for any daytime period. For example, in the morning, south-east facades receive more solar radiation and consequently they experience a higher LST than flat roofs (310-320 K vs. 300-310 K) (Figure 4A). At noon, the roofs are the hottest areas (330-335 K) and most facades are significantly cooler (310-320 K) (Figure 4B). In the evening, the south-west facades receive a high amount of solar solar radiation causing a higher LST in these surfaces than flat roof (320-330 K vs. 310-320 K) (Figure 4C). LST in the evening are generally higher than in the morning due to a higher ambient air temperature (Figure 4C vs. Figure 4A).

4. DISCUSSION

The increasing availability of 3D city models stimulate the need for 3D modeling in urban areas including solar radiation and LST modeling. The usual LST modeling approach based on DSMs approximating 3D structures are often problematic due to a poor representation of vertical surfaces (Kolečanský et al., 2021). The 3D approach presented in this study is based on a vector data format, the v.sun solar radiation module in GRASS GIS and Python version of the lst.stefan-boltzman.sh script.

The advantage of this solution is morphological accuracy and calculation speed. A complex morphology of urban areas cause a strong variation in solar radiation and LST patterns (Lindberg and Grimmond, 2011). As shown in our case studies, these variations are present especially in the morning and evening, when the solar altitude is lower in comparison to the noon situation when the roofs receive large amounts of solar radiation.

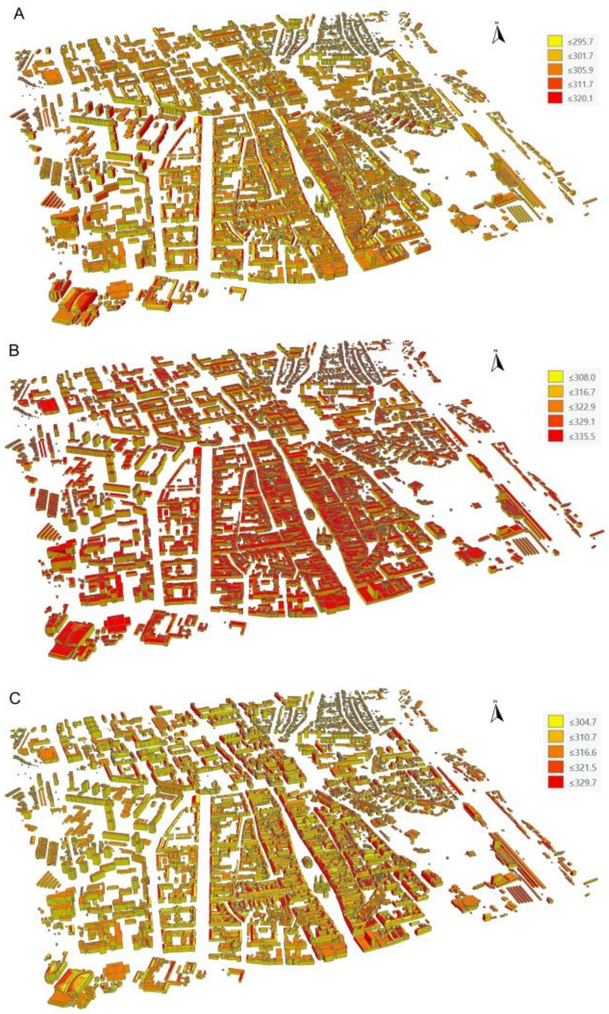

Figure 4. Calculated LST (K) in the city of Košice at A) 7:00, B) 12:00, C) 17:00 on 1 July.

As mentioned above, the presented model does not include a heat storage in urban surfaces. Urban heat storage is an important factor influencing LST (Grimmond et al., 1991; Grimmond and Oke, 1999). In the morning, heat storage accummulates heat in urban materials effectively lowering LST, whereas in the afternoon, heat is released thus increasing LST. The presented approach can modified to include a heat storage factor as shown by Hofierka et al. (2020a). Still, the model is only for a daytime period when solar radiation is available unde clear sky or real sky atmospheric conditions.

In comparison to a traditional approach of estimating LST by remote sensing thermal sensors, this LST modeling approach provides a flexibility to calculate LST for any daytime moment with a excellent spatial accuracy and a level of detail provided by a vector 3D city model. The disadvantage of this approach is a need for a complex data describing thermal properties of urban surfaces, which often are not available. Some input parameters, such as albedo can be derived from satellite or airborne sensors sometimes with a lower spatial resolution. Other input parameters, such as the convection heat transfer coefficient must be derived from other data such as a construction documentation. The thermal effects of urban greenery are difficult to measure and model since they are influenced by an evapotranspiration process and very complex morphological structures of trees.

5. CONCLUSIONS

We have presented a 3D LST model based on open-source solar radiation modeling in GRASS GIS and the Stefan-Boltzmann Law describing the equilibrium temperature for insolated surfaces represented by a 3D city model. The 3D approach improves our understanding of diurnal changes in LST, the impact of urban morphology on LST for specific parts of buildings (roofs vs. facades). This can be used for very effective urban planning and urban heat island mitigation strategies such as increasing albedo for specific urban surfaces, development of green roofs or morphological regulations within the urban development (Ratti et al., 2005; Maimaitiyiming et al., 2014).
The more advanced, comprehensive approach requires the use of the LST model including a heat storage factor and complex 3D data on thermal properties of urban surfaces. Nevertheless, the open-source environment and simple implementation in GRASS GIS provides an interesting LST modeling tool for urban planners or enviromentalists.

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