Verification of Urban Heat Island Microclimatic Model by Using Thermal Remote Sensing Data

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Abstract. The paper deals with the thermal remote sensing data application in verification of Voronezh urban heat island model. We computed surface temperature layer and temperature variation layer for the warm season of 2015 on the basis of Landsat 8 TIRS scenes set. The values from those layers and the urban heat island layer at 234 ground control areas were compared. It validated the urban heat island model for built-up areas and showed the thermal differences for water and forests surfaces. To convert the real surface temperatures to urban heat island scores a regression model was computed. The study reveals that the thermal remote sensing data and the urban heat island model are complimenting each other in case of microclimatic studies in Voronezh.

1. Introduction

Microclimate of urban land has great practical importance in bioclimatology and urban development for human vital activity. Microclimatic mapping of Voronezh city was conducted by I.V. Popova with co-authors [1][2][3][4]. The methods of this microclimatic modeling continue to evolve, but for verification of created models, long-term field studies and special equipment is required. At the same time the important source of information about microclimate, except for field studies, is remote sensing data (RSD) including the survey in thermal area of electromagnetic radiation [5][6][7][8].

In this research, the possibility of using thermal imagery is considered, in order to evaluate a microclimatic model of urban heat island, Voronezh city case. In this paper work the following objectives have been guaranteed:

1. Mapping of the underlying surface temperature in the sampled area, using orbital survey during the warm season.
2. Evaluation of the link between microclimatic model of urban heat island and temperature distribution identified by RSD.

2. Study area and methods

Satellite imagery (multispectral scenes) from Landsat 7, Landsat 8 and Terra Aster were considered as a source of remote data on thermal emission of underlying surface. Comparative analyses of available
scenes let us choose the data from Landsat 8 TIRS (the thermal bands №10 and 11 with 100 meters’ spatial resolution) as the main source of data. Thermal bands of Landsat 7 ETM+ have higher spatial resolution (60 meters per pixel), but these scenes acquired after 2003 have artificial stripes on the image because of the malfunction of the sensor and thus are not meet the research objectives [9][10][11]. Another source of remote data in thermal spectrum is Terra Aster with resolution of 90 meters per pixel was not used because of the low number of cloudless scenes available for the area of interest [12][13][14].

According to the Worldwide Reference System 2, the territory of Voronezh places in the center of Landsat 8 scenes with path № 176 and row № 24. Such scenes of Voronezh for the last 5 years were obtained from U.S. Geological Survey (web-site: http://www.usgs.gov). Only cloudless scenes (cloudiness less 10%) were uploaded from there, carried out during the period from the end of May to the beginning of September. As a result of this selection, it has been established that the most representative set of 5 scenes is available for 2015, while in other years, there are only 2-3 or less images because of the cloudiness in the other survey dates. Thus, Landsat 8 TIRS data for the warm season of 2015 were used in the given research to calculate surface average temperatures. Identifiers of the chosen scenes are listed in the table 1.

Interpretation of the remotely sensed temperatures of the underlying surfaces was conducted with the consideration of the sun angle and the sensor angle to the focused area. Also, the air condition, air temperature and other meteorological parameters, which could affect the temperature of an underlying surface, were taken into account: humidity, wind speed, precipitation.

| №   | Scene identifier                  | Date of the surveya | Meteorological parametersb |
|-----|----------------------------------|---------------------|----------------------------|
| 1   | LC81760242015141LGN00             | May 21             | +22,5                      |
|     |                                  |                     | 2                          |
|     |                                  |                     | 40                         |
|     |                                  |                     | none                       |
| 2   | LC81760242015157LGN00             | June 6             | +19,8                      |
|     |                                  |                     | 5                          |
|     |                                  |                     | 29                         |
|     |                                  |                     | 0,9                        |
| 3   | LC81760242015189LGN00             | July 8             | +25,1                      |
|     |                                  |                     | 5                          |
|     |                                  |                     | 38                         |
|     |                                  |                     | 0,6                        |
| 4   | LC81760242015221LGN00             | August 9           | +29,5                      |
|     |                                  |                     | 2                          |
|     |                                  |                     | 49                         |
|     |                                  |                     | none                       |
| 5   | LC81760242015237LGN00             | August 25          | +20,5                      |
|     |                                  |                     | 3                          |
|     |                                  |                     | 30                         |
|     |                                  |                     | none                       |

The survey within specified dates was done at about 11:17 a.m. local time. 

The set of the scenes was processed with the open source geographic information system QGIS 2.18 and Semi-Automatic Classification Plugin (SCP) with consideration of the data and sensor specifications [15][16] and commonly used methodological approaches [17][18][19][20]. At the first stage radiometric band calibration of the selected scenes and the conversion of digital numbers of thermal brightness into Celsius degrees were accomplished. Then the values of temperatures between bands №10 and №11 in the each scene were averaged with the raster calculator. The output layers were used to calculate mean temperatures and their coefficient of variations at pixels through the whole warm season of 2015.

3. Results and Discussions
As a result, raster layers with 100-meter spatial resolution were created. The layers show distribution of temperatures on the territory of Voronezh city and its environments. The layers display the temperature of underlying surface at the moment of the survey (about 11:17 a.m.) on May 21, June 6,
July 8, August 9 and 25. These layers were stacked into a multi-temporal composite layer, which was used then for calculation of the mean temperature layer and the temperature variance estimation. The layer extents of Voronezh are shown in the generalized form (color ramp with a discrete step) in the figure 1.

The analysis of represented images makes it possible to establish the location of temperature anomalies which includes heat islands. So, extremely high surface temperatures (35-40°C) in Voronezh during the warm season has stably been observed only in industrial plant areas: Voronezh Mechanical Plant JSC “SRPSC” by Khrunichev, Public JSC “Tjazhmekpress”, Voronezh Carriage Renovating Plant JSC “VCRP”, Public JSC “Voronezh Tire Plant”, buildings 43 and 45 Public JSC Voronezh Aircraft Production Association, Private JSC “Voronezh Bridge Construction Plant”, Private JSC “Rudgormash”, folding complex “Kaskad”.

![Figure 1. Maps of mean temperature (t) distribution and temperature variance (V) in Voronezh for the warm season of 2015. The objects marked with the numbers 1-3 are described in the text below.](image)

Temporal changes of temperature field can be analyzed as well. So, the raster of variation coefficients shows general stability of the surface temperatures in Voronezh through the survey moments within the study season, except for the local areas with temperature variations up to 15-30%. Those thermally unstable areas correspond to the underlying surface which can alter during a season. There are three types of such surfaces (the numbering follows 1-3 in figure 1):

1. Croplands, where the emission of heat was changing during the season, depending on a crop species, cultivation and vegetation stages.
2. Filtration fields of disposal works, which thermal regime depends on waste effluents input.
3. The southern part of Voronezh Reservoir, which is exposed to annual explosion of blue-green algae and because of that the albedo alterations.

The given territories with unstable underlying surfaces, where temperature variations were more than 15% (fig.1, 1-3 numbers) were excluded from the further analysis (computing of zonal statistics for different types of underlying surfaces of ground control areas). The ground control areas are represented by the core areas (from 5 hectares and more) of the largest patches of different land-use
class. In overall, 234 ground control areas were allocated in sampled area: 102 residential development control areas with a total area of 2213 hectares, industrial areas (802 hectares), forest cover areas (4583 hectares) and 8 water areas (3638 hectares) (figure 2).

![Figure 2. On the left: the microclimatic map of Voronezh urban heat island [4]; on the right: the map of ground control areas of different surface types.](image)

Samples of mean values of temperatures and scores of heat island intensity, accompanied by standard deviations of both variables were calculated for each of 234 ground control areas. Descriptive statistics for the obtained variables show significant thermal differences among the tested types of underlying surfaces sampled by the ground control areas (figure 3). The both measures, the scores of heat island intensity and the actual values of mean temperatures, give the highest meanings to industrial and residential areas and the lowest ones to forested areas. However, the scores of heat island do not represent any significant differences between the industrial and residential areas. As for the evaluation of water areas thermal regime, there are divergences: by the fact, water surface is the coldest object in the sampled area, but it has mean scores of heat intensity. That is because of microclimatic model is devised for evaluation of urban heat island and is not adjusted for water areas. So for the further correlation analysis of the given variables, the data from 8 ground control areas on water surfaces were excluded.

Spearman’s rank correlation coefficient (ρ) between the scores of urban heat island and remotely sensed temperatures for the warm season of 2015 is equal +0.65 (n = 226 ground control areas). This significantly positive statistical correlation verifies the tested urban heat island model. Although the identified discrepancy exists due to the tested microclimatic model is based on a set of indirect measures [1][2][3][4] and the referential temperature layer is the result of averaging values, which can differ from long-term mean temperatures for interested season.
Figure 3. Box plots of mean temperatures range (on the left) and mean scores of heat island intensity (on the right) for different types of underlying surface: a – residential development, b – industrial, c – forest cover, d – water areas.

Nevertheless, the identified relationship between scores and temperatures can be approximated by a linear regression:

\[ Y = 0.75 \times X - 15.77, \]  

where \( Y \) is the score of heat island intensity and \( X \) is the mean temperature of underlying surface by remote data (\( R^2=0.52 \), coefficients are significant by F-test, \( p<0.05 \)).

The nature of data and features of its dispersion allow to apply Poisson regression:

\[ Y = 0.005 \times \exp(0.319 \times X) \]  

Graphical representation of the used regression models is given in the figure 4.

Figure 4. Diagram of regression models to link the heat island intensity scores and mean temperatures of an underlying surface.

Derived equations allow to approximately estimate the score of heat island intensity by the value of mean surface temperatures, what may be required for the microclimatic differentiation of the city. In turn, the scores can be converted in theoretical temperature values, what can be used for sharpening the resolution of the remotely sensed thermal map. The original map resolution is defined by the used bands. In our case, that is 100 meters per pixel, while the microclimatic map resolution is 10 meters, so
one pixel of the temperature raster encompasses about 100 pixels with the hit island scores. Thus the given microclimatic model has a potential to significantly optimize the thermal images.

4. Results and Discussions
Therefore, Landsat 8 TIRS scenes were applied for the verification of the urban heat island microclimatic model in the given research. Mapping of underlying surface temperature by RSD for the warm season of 2015 let us identify stable thermal anomalies for industrial areas and high temperature variation areas in Voronezh (croplands, water enrichment zone and other). Generally, for residential, industrial and forested areas, stable curves of temperature have been observed within considering season. Correlation and regression analyses of the heat island intensity in relation to mean temperatures of different surface types at the ground control areas verified the microclimatic model. The study reveals that the thermal remote sensing data and the urban heat island model are complimenting each other in case of microclimatic studies in Voronezh.

5. References
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