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# Urban heat island effects over Krasnoyarsk obtained on the basis of Landsat 8 remote sensing data

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**Abstract.** Land surface temperature anomalies are typical for all major cities in the world. Satellite data in the thermal infrared range are a powerful source of information for analyzing and determining of temperature anomalies. Determination of the nature and boundaries of temperature anomalies will help to understand the causes of the unfavorable ecological situation in Krasnoyarsk: where, in addition to high industrial emissions, the atmospheric processes also exert their influence, which may cause the impurities linger and concentrate over the city. This paper presents a technique for monitoring the land surface temperature on the basis of thermal infrared data from the 10th band of Landsat 8 satellite. Ground-based temperature data from an environment protection state regional system for observing the state of the atmosphere in the Earth's surface layer are used. The results show that the temperature in the places of temperature anomalies is 5-8 degrees higher than the average surface temperature of the city. Based on the results of an analysis of summer thermal multi-temporal space images, several thermal zones of different nature are outlined in the territory of the city.

## 1. Introduction

The temperature at the Earth's surface can be estimated by ground-based methods or satellite remote sensing data. Satellite remote sensing is the only means of obtaining long-term homogeneous series of land surface temperature (LST) data. The network of ground-based observations is usually quite rare, and so it is important to obtain information by remote methods. From the values of the thermal infrared spectral bands it is possible to determine the radio brightness temperature of the underlying surface. The compilation of temporal temperature series of the land surface is useful for solving a large number of scientific problems. The information obtained during the survey of the Earth in the thermal range can be used in geographic science in two main directions. In the first case, thermal radiation is an indicator of objects, phenomena, and processes that are hidden from direct observation, and in the second case, the thermal radiation itself, which is important in climate change matters, is of interest.

This paper presents the results of investigations of LST anomalies in the city of Krasnoyarsk (Russia) and its suburban area. The urgency of the task is due to the peculiarities of the city with a population of more than a million people, which is located 40 km below the hydroelectric power station (HPS) on the Yenisei River. Due to HPS the Yenisei River running through the city does not freeze even in severe winters, thus acting as a strong heat and evaporation island. Conversely, in summer the river is unusually cold.

We used information from Landsat 8 satellite, namely Thermal InfraRed Sensor (TIRS) and Operational Land Imager (OLI) data, which have 100-m and 30-m resolution, respectively. Ground-based temperature data from the environment protection state regional system for observing the state of the atmosphere in the Earth's surface layer were also used.

## 2. Urban heat island over Krasnoyarsk

In recent years the relationship between the use of urban land and environmental quality has received increased attention in both research and planning [1]. In this regard, the urban climate looms large as one of the most important parameters, and cities play an important role in increasing the impact of the urban climate. Built-up areas look like uneven artificial landscapes with building materials, partially different from the natural surfaces. In addition, anthropogenic processes release excess heat and pollution to the surrounding air. Together they lead to a higher urban temperature compared to a relatively natural environment.

Recently special attention was paid to urban heat islands (UHIs) [2–4]. The effect of increasing the temperature of the environment is observed in large cities, where the air temperature throughout the year is several degrees higher than in the adjacent areas.

The problem of temperature anomalies is typical for all major cities in the world. Space thermal images are a powerful source of information for analyzing and forming temperature anomalies within a single territory [5]. Determination of the nature and boundaries of temperature anomalies will help to understand the causes of the unfavorable ecological situation in Krasnoyarsk: where, in addition to high industrial emissions, the atmospheric processes influence, which causes the impurities to linger and concentrate over the city.

Krasnoyarsk is a large industrial center with unique natural and climatic features caused by the terrain conditions and thermal heterogeneity of the terrain. Krasnoyarsk is classified as having a high potential for atmospheric pollution. The valley-like relief of the terrain, high frequency of fogs and vapor over the Yenisei lead to the accumulation of harmful impurities above the main territory of the city.

Krasnoyarsk is located at the junction of three geomorphological countries: the West Siberian Plain, the Central Siberian Plateau, and the Altai-Sayan Mountainous Country. Krasnoyarsk is located on two banks of the Yenisei River. Construction of a hydroelectric power station on the Yenisei River led to no freezing during the cold season. The air temperature in winter reaches values below -30°C. The formation of temperature anomalies in the city is affected by the large temperature difference between the nonfreezing Yenisei and the surrounding area. Thus, the interaction of the two effects of temperature anomalies adversely affects the ecological situation in the city [6]. Therefore, it is important to observe temperature anomalies at different times of the year using remote sensing data; there are ample opportunities for research in this field.

## 3. Thermal infrared data satellites

The assessment of the land surface temperature by satellite data has been carried out since the 60s of the 20th century. For this purpose, remote sensing data of the thermal infrared (IR) range are used, on whose basis the land surface temperature is calculated. In particular, since 1970, the year of operation of satellites of the NOAA series (USA), on which a scanning high-resolution radiometer AVHRR is mounted, which measures the reflectivity of the Earth in 5 spectral bands, including the thermal infrared one. The main purpose is to monitor the cloud cover and measure the outgoing thermal radiation of the Earth [7]. Landsat data are used to estimate the land surface temperature [8].

The currently existing satellite systems provide data in the IR spectrum range with various frequency and level of detail: from daily with a spatial resolution of 1 km/pixel to weekly with a spatial resolution of about 100 m/pixel; the temperature measurement accuracy is 1-2 degrees [9].

Data of the MODIS radiometer installed on the American Terra and Aqua satellites are widely used. It performs daily surveys with a spatial resolution of 1000 m in 36 spectral channels, among which are channels of the thermal infrared range. The land surface temperature is one of the standard MODIS information products [10].

The American Landsat program began in 1972, and since that time eight satellites were launched. Since Landsat 4 was launched in 1982, the satellites of this program have been shooting in the thermal infrared range [11].

The Landsat 8 satellite works on orbit since 2013; it acquires data using two different sensors: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). In general, Landsat 8 images consist of 11 spectral bands, where the 10th and 11th ones are in the TIR spectrum range with a spatial resolution of 100 m, which allows them to analyze the energy of the Earth's surface rather than the reflection of sunlight. Recorded data of the TIR channels are converted into the brightness temperature, and, in turn, into the land surface temperature. The calculation of emissivity is an integral part of the final stage.

Landsat satellite series data appear to be most attractive due to a combination of the technical characteristics, the availability of received information, and the availability of a multi-year archive of observations.

## 4. Satellite data based temperature

The temperature of the Earth's surface characterizes the interaction between the atmosphere and the surface. Knowledge of the land surface temperature is required for a variety of scientific studies, including climatology, hydrology, and ecology. In particular, the temperature data are necessary for solving tasks such as estimation of the soil moisture, detection and prediction of frost, and monitoring of crops. The temperature of the earth's surface is also one of the indicators of anthropogenic impact on natural resources [12]. Regular monitoring of the temperature allows one to analyze the surface temperature and assess its variability.

Remote sensing is the only instrument of obtaining long-term homogeneous series of data on the temperature of regional and global coverage. The need to obtain regular satellite data on the land surface temperature is dictated by the fact that the network of ground observations is quite rare.

From the values of the thermal channels, it is possible to determine the radio brightness temperature of the underlying surface. Instead of measuring the air temperature, as weather stations do, satellite systems measure the land surface temperature, which is often higher. Theoretically, the accuracy of the temperature estimation is about 0.5°C, however, haze in the atmosphere understates the values by several degrees. The initial data for determining the temperature are the values of the intensity of the radiation coming to the sensor of the satellite and registered by the corresponding thermal channel. Based on the values of these thermal channels, we calculate the value of land surface temperature using the formula [13]

$$\mathrm{T} = T_B/[1 + (\lambda \cdot T_B/\mathrm{c}_2)\cdot ln(e)], \qquad (1)$$

where $T_B$ is the At-Satellite Brightness Temperature (K),
$\lambda$ = the wavelength of emitted radiance,
$\mathrm{c}_2 = h\cdot c/s = 1.4388\cdot 10^{-2}$ m K,
$h$ = Planck's constant = $6.626\cdot 10^{-34}$ J s,
$c$ = the velocity of light = $2.998\cdot 10^{8}$ m/s,
$s$ = Boltzmann constant = $1.38\cdot 10^{-23}$ J/K,
$e$ = the emissivity of the surface.

At present there are two main methods for determining the emissivity from satellite data. The first method uses a classification of objects in the image where each class is assigned a specific value of the radiation coefficient (Table 1), and in the second one it is determined on the basis of the *NDVI* index. The first method is easier to use, but its accuracy is limited and depends on the effectiveness of the classification results of the image. The second method has a higher accuracy and allows one to calculate the surface emissivity for each pixel in the image.

Consider the first method in more detail, where the first step is to determine the surface type, the entire area is divided into four classes: water, open soil, vegetation, and buildings. After the classification of the image, each class corresponds to the value of the emission factor, which is presented in Table 1 (the values used are approximate, since the radiation coefficient of each material must be obtained from field survey):

**Table 1.** Correspondence between the land cover classification and the emissivity values.

| Land surface | Bare oil | Vegetation | Built-up | Water |
|---|---|---|---|---|
| Emissivity | 0.928 | 0.982 | 0.942 | 0.98 |

The second method has higher accuracy and allows one to calculate the surface radiation coefficient for each pixel of the image. Consider the second method of determining the radiation coefficient based on the normalized vegetation index *NDVI*.

Correct determination of the surface temperature is limited to an accurate knowledge of the emission factor. The relationship between the surface temperature of the earth and the *NDVI* takes into account that vegetation and soils are the main surface:

$$\varepsilon = a + b \cdot \ln(NDVI), \tag{2}$$

where a = 1.0094 and b = 0.047 are obtained by a regression analysis based on a large dataset.
To determine the *NDVI*, the red spectral ranges and the near infrared ranges of the spectrum are used:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}, \tag{3}$$

where $\rho_{NIR}$ is the reflection in the near infrared and $\rho_{RED}$ is the reflection in the red spectrum range.

As to the input satellite data, 10 cloudless scenes from Landsat 8 are used as materials for investigating the thermal features of the territory of Krasnoyarsk. These scenes are acquired during the snowless period from 2013 to 2016.

We use the first mentioned method (i.e. image supervised classification) for calculating the emissivity to obtain the land surface temperature in our study. Several GIS operations are required to implement it, but much less computations than to implement the second method.

## 5. Source satellite data and software

The materials for the study of the thermal characteristics of the city of Krasnoyarsk are 15 Landsat 8 scenes. The selected 15 cloudless scenes in the snow-free period from 2013 to 2017: 07.07.2017, 07.08.2017, 22.07.2017, 29.06.2017, 20.06.2017, 28.05.2017, 07.10.2016, 05.09.2016, 10.06.2016, 23.04.2016, 17.07.2015, 01.07.2015, 08.06.2015, 14.05.2015, 07.07.2014, and 18.06.2013.

The earth surface temperature is calculated from satellite remote sensing data using the values of the 10th channel Landsat 8, past the stage of radiometric and atmospheric correction. The calculations are performed in the free software QGIS 2.18. For atmospheric correction of the satellite data and further calculations, the Semi-Automatic Classification Plugin (SACP) is used [14].

We should especially mention the method of using a combination of different data from different satellites to increase the spatial resolution. This approach is becoming popular now [15]. On the one hand, we use Landsat multispectral data, which have a resolution of 30 meters. Note that initially the Landsat TIRS radiometer performs infrared imaging at a resolution of 100 m, and then these data are immediately interpolated into a resolution of 30 meters corresponding to the rest of the Landsat channels, for convenience of their use. On the other hand, satellite data of higher resolution than Landsat can be used to calculate the *NDVI* indices, whose values are required to determine the temperature, as indicated above. We used PlanetScope high-resolution images with a spatial resolution of 3 m to create the image classification. The infrared data have also been interpolated to this resolution. As a result, temperature maps with a spatial resolution of 3 meters were obtained.

The PlanetScope satellite constellation formed by the Planet company from 2013. To date there are about 200 operating remote sensing PlanetScope satellites on the orbit. The frequency of obtaining images reaches 2-7 times a week, while in many areas shooting is performed almost daily. The PlanetScope satellites are shooting in 4 main spectral channels with 3-4 m spatial resolution [16].

## 6. Results and discussion

The land surface temperature is calculated by formula 1. The obtained temperature values are converted to degrees Celsius and based on the obtained values we make for each survey date a temperature map of the land surface, for example, May 28, 2017 (Figure 1).

Figure 1 shows that the temperature of the river is much lower than the surface temperature of the urban areas, forests, and mountains. This low water temperature is due to the construction of a hydroelectric power station on the Yenisei River, twenty-seven kilometers from Krasnoyarsk, which had a great impact on the distribution of seasonal temperatures in the city and its suburbs.

Changes in the thermal regime of the river as a result of the construction of hydraulic structures in comparison with the natural conditions affect the operation of not only the hydroelectric power station, but also the water management facilities, water transport, as well as the water quality and climate. Regardless of the annual cycle period, characteristic changes in the water temperature occur downstream. Namely, the water temperature in Yenisei in the area of Krasnoyarsk in summer is 8-10°C lower than before the river regulation, and, on the contrary, increases by 4-5°C in the autumn months, which caused some difficulties in the development of the surrounding area and had a significant impact on the climate of Krasnoyarsk [6].

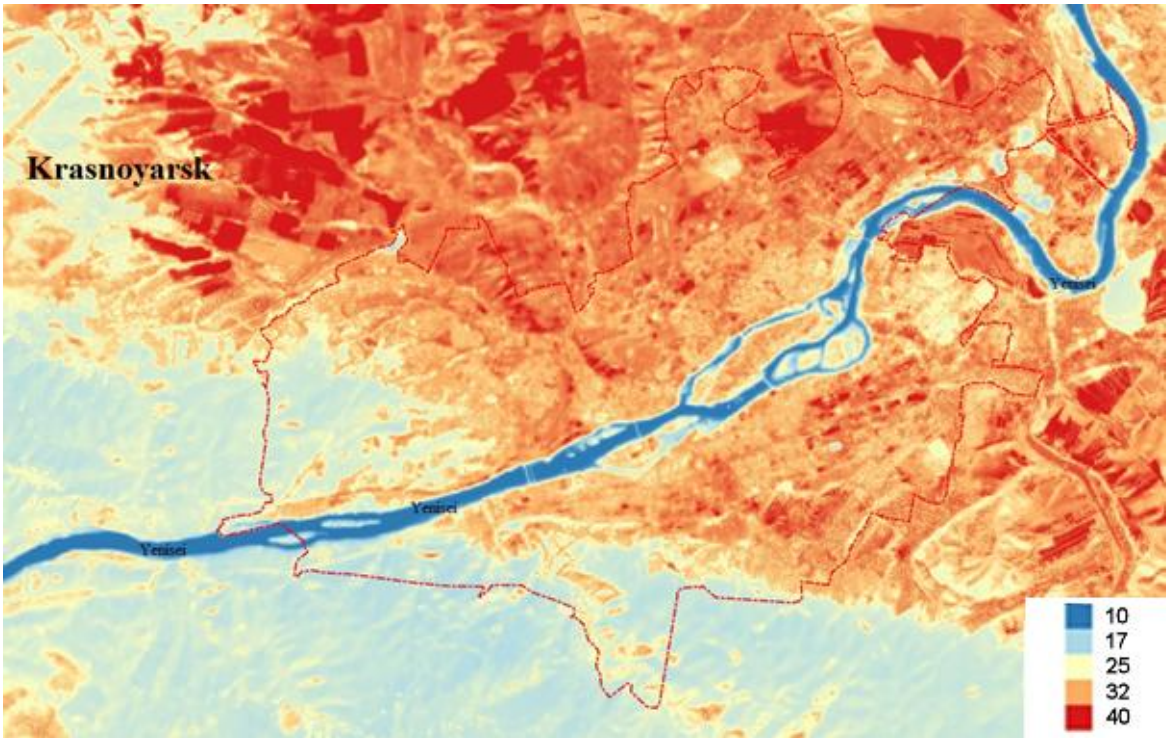


**Figure 1.** Surface temperature of the Krasnoyarsk city (28.05.2017).

Due to the fact that temperature anomalies may differ in different seasons of the year, the study was performed for images grouped by seasons of the year; this approach is widely used in practice [17]. To find the maximum temperature values within the city, all images were distributed over three seasons: summer, spring, and autumn. The boundaries of thermal anomalies were formed for spring, summer, and autumn images.

In order to assess the use of satellite images to determine the temperature, the values of the earth's surface temperature and the air temperature were compared at three points of the city where automatic weather stations (AWS) are located. An approach in which remote sensing data are investigated in conjunction with ground-based observations is widely used now [18]. The temperature presented in the table is fixed on the AWS at 12 PM, which is as close as possible to the time of flight of the Landsat 8 satellite over the city of Krasnoyarsk (Table 2).

**Table 2.** Comparison of temperature data obtained on automatic weather stations (AWSs) with remote sensing data calculated on the basis of Landsat imagery (RS).

| Date | AWS-1 Dudiskaya | AWS-2 Minusinsk. | AWS-3 RoevRuch. | RS-1 Dudiskaya | RS-2 Minusinsk. | RS-3 RoevRuch. |
|---|---|---|---|---|---|---|
| 28.05.2017 | 20.4 | 19 | 20.3 | 31.2 | 29.71 | 24 |
| 20.06.2017 | 28.5 | 28 | 30.2 | 31.96 | 33.44 | 33.22 |
| 29.06.2017 | 26.1 | 25 | 27.6 | 32.26 | -- | 27 |
| 22.07.2017 | 22.4 | 22 | 23.4 | 24.59 | -- | 23.9 |
| 07.08.2017 | 29.5 | 29 | 29.9 | 31 | 30 | 27.57 |
| 07.10.2016 | 5.4 | 3 | 0.4 | 7 | 3 | 2 |
| 05.09.2016 | 16.3 | 15 | 17,6 | 22 | 19 | 19 |
| 10.06.2016 | 25 | 23.4 | 26.1 | 33 | 25 | 28 |
| 23.04.2016 | 15.1 | 12.2 | 15.4 | 22 | 19 | 18 |
| 17.07.2015 | 24.6 | 23 | 26 | 34 | 24 | 29 |
| 01.07.2015 | 30.4 | 28 | 30.9 | 34 | 29 | 29 |
| 08.06.2015 | 24 | 22.6 | 24.9 | 30 | 25 | 27 |
| 14.05.2015 | 19.8 | 18.5 | 21.7 | 25 | 24 | 27 |
| 07.07.2014 | 29.1 | 27.3 | 30.3 | 32 | 27 | 31 |
| 18.06.2013 | 29.9 | 27 | 21.1 | 33 | 34 | 21 |

The difference between the values obtained with the AWS and satellite data, due to the fact that the AWS measured temperature values at a height of 2 meters from the earth’s surface, and in the case of satellite data is calculated directly the land surface temperature.

After consideration of a set of summer images, thermal anomalies were formed for each image. Further, to determine the thermal anomalies of the city, multiple intersections of anomalies were found in six summer images, and a polygonal layer of anomalies was formed.

Anomalies were formed from the areas where the earth's surface temperature is higher by 5-8 degrees than the average surface temperature. When forming the boundaries of thermal anomalies, anomalies up to 100×100 meters were removed to eliminate single artifacts in the satellite imagery; for example, small structures with metal roofs can create additional thermal anomalies. The maximum temperature values obtained are shown in Figure 2.

In the obtained map of summer maximum temperature values in the territory of Krasnoyarsk it is possible to distinguish two types of thermal anomalies: natural and anthropogenic. The anomalies on the natural hills with the southern and South-Western exposure of the slope are well discernible, for example, in the Zheleznodorozhny district of Krasnoyarsk.

The highest surface temperature is the Karaul’naya gora (mountain) with a thick slope vegetation cover. Apart from natural ones, it is worth considering anomalies that arise as a result of anthropogenic transformation of the environment. Most often they are formed near shopping centers that occupy a large area and industrial districts of the city.

Let us consider some of the anomalies in more detail. Anomalies are observed in the territory near the city central railway station, on the railway tracks, in the territory of the Combine plant that is not working. Thermal anomalies on the right bank of Krasnoyarsk are observed where the predominant industrial zone is located: Krasnoyarsk Machine-Building Plant, Thermal Power Plant No 1, and Siberian Plant of Heavy Machinery. In the Sovetsky district of the city (Figure 3) located on the left bank the maximum temperatures prevail in the industrial zone of the city, as well as in places of congestion of shopping centers. Thermal anomalies which correspond to shopping centers: The Planet Mall, Lenta Hypermarket, a number of shopping and entertainment centers, Car showrooms (Toyota Center Krasnoyarsk, Porsche Center Krasnoyarsk, Audi Center Krasnoyarsk, Ford Center Krasnoyarsk).

The described thermal anomalies indicate thermal pollution of the city, which can be determined by satellite remote sensing. Therefore, it is important to choose a right method for determining the land surface temperature on whose basis thermal anomalies are detected. This paper describes two methods for determining the emission factor required to calculate the surface land temperature.

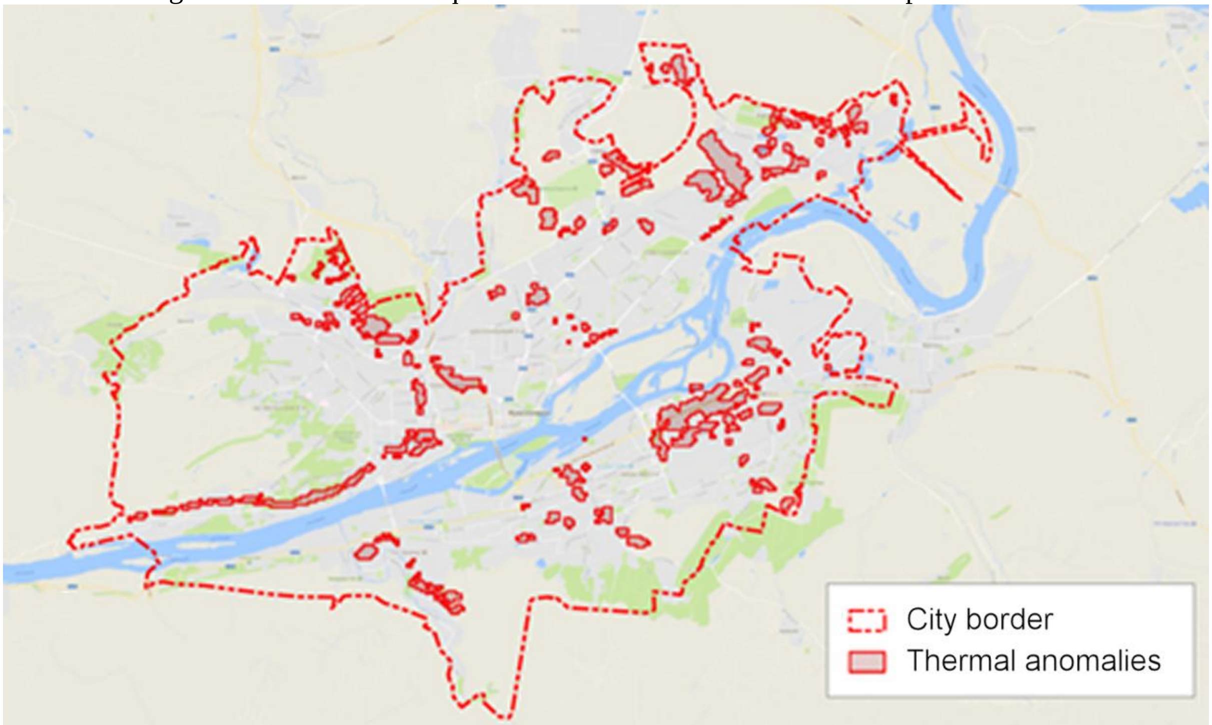


**Figure 2.** Summer distribution of maximum temperature values.

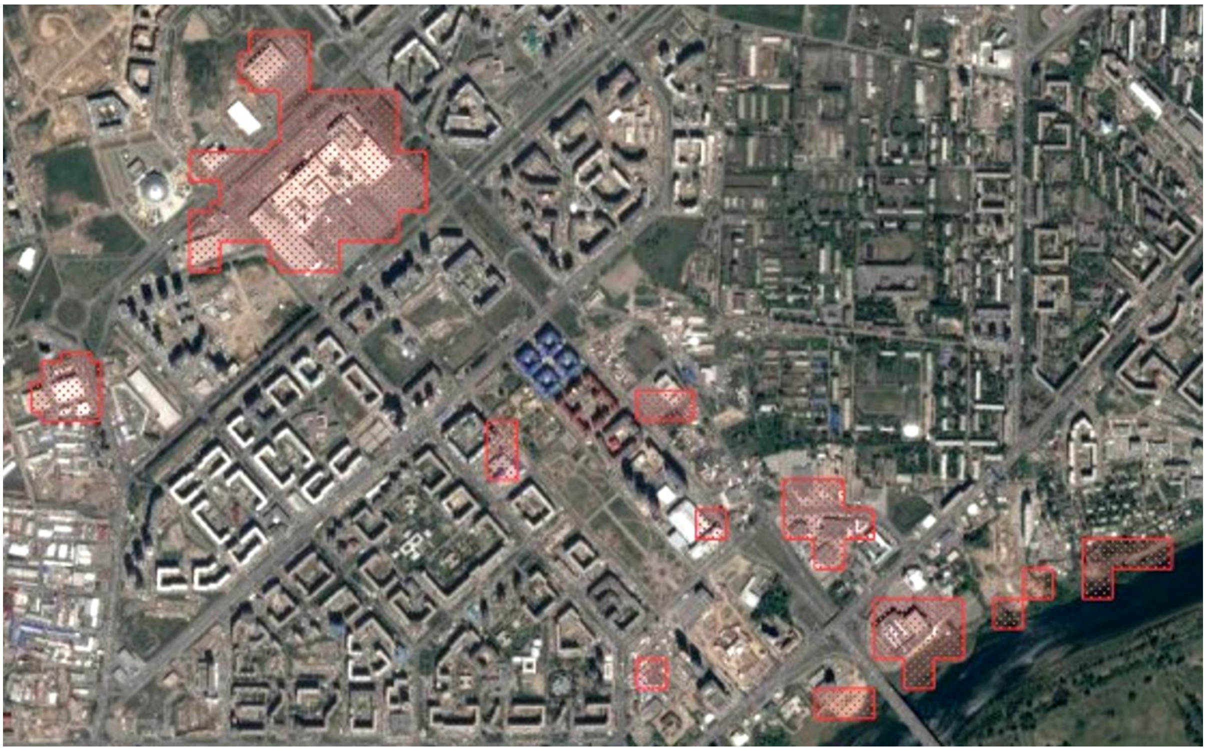

**Figure 3.** Thermal anomalies at Sovetsky district of Krasnoyarsk.

Maps of thermal anomalies informatively must be in the territory with a large number of objects with intense heat radiation. In our work such objects were industrial enterprises and shopping centers. These objects consist of dense materials with high heat capacity, such as asphalt, concrete, reinforced concrete, and stone. Most of the anthropogenic objects (houses, industrial premises, shopping and entertainment centers) which form thermal anomalies are built of such materials. The larger the surface area of such objects, the more intense the radiation and, therefore, the greater the impact on the environment.

Figure 4 shows a graph based on data from Table 2. It can be concluded that the temperature obtained on the basis of satellite images is often slightly higher than the values obtained at ground stations.

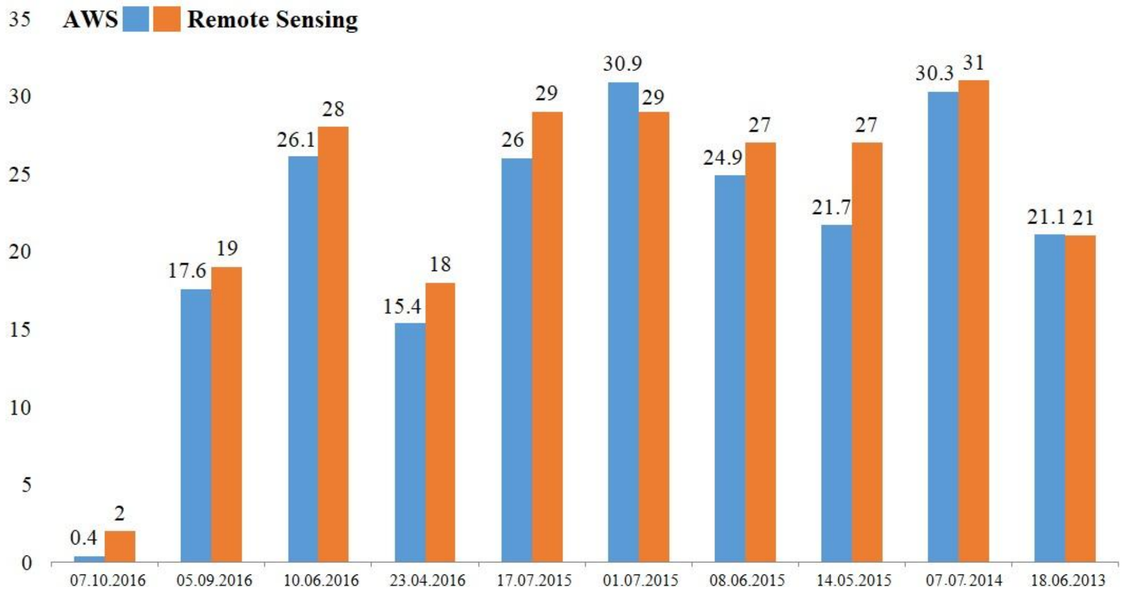


**Figure 4.** Comparison of temperature measured at an automatic weather station with temperature calculated from remote sensing data at RoevRuch. city point.

## 7. Conclusions

This work carried out a calculation of land surface temperature for 15 cloudless scenes of Landsat 8 satellite from 2013 to 2017. The calculation was made in 2 steps, to determine the emissivity. A method with the determination of a surface type by the user in a classification of the images was chosen. To increase the quality of the spatial resolution for the first time we used a classification of the multi-channel data PlanetScope. At the second step, the temperature of the land surface was calculated using the temperature of spectral radiation brightness and the emissivity. An analysis of the thus obtained values of the earth's surface temperature allowed us to form the boundaries of thermal anomalies. For further analysis of the city, the thermal anomalies have been formed by the season. The summer thermal images are most diverse: they identify industrial facilities, residential areas, forests, water bodies, and open ground areas.

Thermal anomalies in the territory of industrial zones, landscape hills and anomalies corresponding to the location and form of shopping centers have been found in the analysis of the images.

The difference between the air temperature obtained by an AWS and the land surface temperature calculated on the basis of satellite data may reach several degrees. It should be noted that sometimes the difference between the land surface temperature and the AWS may be sharp, since we compare two different temperatures in different places (the AWS is between 1.1 and 2.0 m from the ground). But despite the difference in the measurements, this technique provides great scope for researchers to explore areas that are not equipped with AWSs but are in the coverage area of Landsat 8.

Of particular interest on the left and right banks of the city of Krasnoyarsk are the industrial zones due to their vast area. In the future the thermal anomalies can be a valuable material for ecological and geographical studies of the territory.

## References

[1] Stone J and Rodgers M 2001 Urban form and thermal efficiency: how the design of cities influences the urban heat island effect *APA Journal* **67** 186-98

[2] Sharma R and Joshi P 2014 Identifying seasonal heat islands in urban settings of Delhi (India) using remotely sensed data – An anomaly based approach *Urban Climate* **9** 19-34

[3] Effat H and Hassan O 2014 Change detection of urban heat islands and some related parameters using multi-temporal Landsat images; a case study for Cairo city, Egypt *Urban Climate* **10** 171-88
[4] Sheng L, Tang X, You H, Gu Q and Hu H 2017 Comparison of the urban heat island intensity quantified by using air temperature and Landsat land surface temperature in Hangzhou, China *Ecol. Indicators* **72** 738-46
[5] Lu D and Weng Q 2006 Spectral mixture analysis of ASTER images for examining the relationship between urban thermal features and biophysical descriptors in Indianapolis, Indiana, USA *Rem. Sens. of Env.* **104** 157-67
[6] Hrebtov M and Hanjalić K 2017 Numerical study of winter diurnal convection over the city of Krasnoyarsk: effects of non-freezing river, undulating fog and steam devils *Bound. Layer Meteo.* **163** 469-95
[7] Stathopoulou M and Cartalis C 2009 Downscaling AVHRR land surface temperatures for improved surface urban heat island intensity estimation *Rem. Sens. of Env.* **113** 2592–605
[8] Giannini M, Belfiore O, Parente C and Santamaria R 2015 Land surface temperature from Landsat 5TM images: comparison of different methods using airborne thermal data *J Eng. Sci. Tech. Rev.* **8** 83-90
[9] Niclos R, Valiente J, Barbera M and Caselles V 2014 Land surface air temperature retrieval from EOS-MODIS images *IEEE Geosci. Rem. Sens. Let.* **11** 1380–84
[10] Merlin O, Duchemin B, Hagolle O, Jacob F, Coudert B, Chehbouni G, Dedieu G, Garatuza J and Kerr Y 2010 Disaggregation of MODIS surface temperature over an agricultural area using a time series of Formosat-2 images. *Rem. Sens. of Env.* 2010, 114, 2500–12
[11] Fu P and Weng Q 2016 Consistent land surface temperature data generation from irregularly spaced Landsat imagery *Rem. Sens. of Env.* **184** 175-87
[12] Lu D and Weng Q 2006 Spectral mixture analysis of ASTER images for examining the relationship between urban thermal features and biophysical descriptors in Indianapolis, Indiana, USA *Rem. Sens. of Env.* **104** 157167
[13] Weng Q, Lu D and Schubring J 2004 Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies *Rem. Sens. of Env.* **89** 467-83
[14] Congedo L 2016 Semi-Automatic Classification Plugin Documentation. DOI: http://dx.doi.org/10.13140/RG.2.2.29474.02242/1
[15] Weng Q, Fu P and Gao F 2014 Generating daily land surface temperature at Landsat resolution by fusing Landsat and MODIS data *Rem. Sens. of Env.* **145** 55–67
[16] PlanetSope satellite imagery. Available at: https://www.planet.com/products/explorer/
[17] Ho H, Knudby A, Sirovyak P, Xu Y, Hodul M and Henderson S 2014 Mapping maximum urban air temperature on hot summer days *Rem. Sens. of Env.* **154** 38-45
[18] Windahl E and Beurs K 2016 An intercomparison of Landsat land surface temperature retrieval methods under variable atmospheric conditions using in situ skin temperature *Int. J Appl. Earth Obs. Geoinf.* **51** 11-27