Using satellite images to study urban heat island and environmental monitoring

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Abstract. The paper describes a number of simplified methods of mapping of the urban environment surface temperature in order to study the structure of the urban heat island. It is very important to take into account the climatic and environmental variables of the territories when planning modern cities and settlements. To solve such problems, methods of remote sensing data are used increasingly. The study of multispectral satellite images provides more information about the characteristics of objects on the earth's surface, as well as data on the distribution of various types of land use. Maps of the earth's surface temperature (LST) can be used for studying the urban microclimate and localization of temperature anomalies of the city, as well as for urban planning tasks. The article considers the operation of processing a series of satellite images of urban areas for the summer period, followed by the study of temporary changes in the temperature portrait of the city. The paper considers the use of semi-automatic methods for obtaining satellite images in the thermal field, as well as a separate study of images in the near-infrared field to search for bright point sources of heat. Radiometric and atmospheric correction was performed on satellite data using the QGIS package and the Semiautomatic Classification Plugin extension. Based on the results of the study, thermal anomalies were localized in the city, and the boundaries of the heat footprint of new neighborhoods were determined.

1. Introduction

Nowadays the so-called "urban heat island" effect is becoming more pronounced in almost all major cities or industrial agglomerations, characterized by the appearance of zones of thermal anomalies with high surface temperatures. The anthropogenic impact on the urban heat island effect is expressed in the form of dense development and the land surface covering materials that actively absorb heat radiation, as well as in reducing the landscaping in the central parts of the city. It is very important to take into account the functions of green planting in cities in order to develop a competent, science-based strategy for the development of the green planting system in the process of urban planning [1]. The urban heat island effect has a significant impact on modern metropolises [2]. During periods of extreme heat this effect leads to increased heat stress and associated mortality[3], as well as to an increase in energy consumption for air conditioning.

Thus, the effect of the urban heat island is one of the important problems that arise in the planning and development of cities and its study can be linked to the more general tasks of studying and optimizing the urban microclimate. The microclimate of a modern city can change very sharply in...
relatively small areas, creating so-called thermal anomalies. Such anomalies can include industrial enterprises or waste landfills.

To compensate for the climatic parameters of territories, there are a number of methods that include both classic gardening methods and more progressive and comprehensive measures. For example, optimization of the territory's aeration regime[4] can have a significant impact on the amount of exhaust gases and average air temperature in urban canyons.

Thus, the study of the urban heat island can be characterized as the collection and processing of long-term data on the thermal structure of the city for subsequent assessment of the impact of temperature anomalies on changes in the microclimate parameters of territories. For these purposes, it is very important to obtain a complete and detailed map of the surface temperature of the urban environment over a wide time interval, taking into account inter-seasonal differences. Currently, for this purpose, data from remote sensing of the earth with the help of space satellites are increasingly used.

Currently, existing remote sensing systems allow observing the earth's surface in a wide spectral range[5]. Special processing of such images allows you to obtain maps of the earth's surface temperature or LST-maps (land surface temperature). Images from modern space satellites such as Landsat and ASTER have high spatial and temporal resolution and can be used for city-level research.

The article considers the process of obtaining a Chelyabinsk LST map for a summer period with a long-term difference for analyzing changes in the thermal structure of the city. Thermal images from ETM+ and TIRS sensors of Landsat-series satellites were used in the work with the application of radiometric and atmospheric correction and surface type classification. Additional analysis of images from the near-infrared satellite's spectral bands was also carried out in order to detect small point heat sources hidden from observation.

2. Materials and methods of research

Currently, due to their high requirements for the quality and uniformity of temperature data, researchers are increasingly using satellite multispectral images to solve problems related to the description of the urban heat island and the study of thermal anomalies[6].

This work is aimed at reviewing modern simplified methods for obtaining surface temperature maps for the study of the urban heat island of Chelyabinsk. This city is a major industrial center and has a high level of industrial emissions and generally unfavorable environmental conditions[7]. The density of buildings and the proximity of industrial enterprises to the city center, combined with the flat terrain type, lead to a high concentration of harmful pollutants over the Central part of the city and the appearance of smog. The suboptimal orientation of new neighborhoods in terms of wind conditions further worsens the aeration regime of buildings and, as a result, environmental and climatic comfort in the zone of development[8]. As data for analyzing the structure of the heat island of Chelyabinsk, we used summer daytime images of the territory in the thermal range with a difference of more than 10 years to record changes in the thermal portrait of the city.

Currently, there are a number of satellite systems that allow observations of the earth's surface in different spectral ranges, while only a few devices have a thermal channel for shooting and allow you to obtain temperature images of the surface. At the same time, for observations on a city scale, high spatial resolution of images is required, about 100 m per pixel of the image, so systems for conducting global observations, such as the MODIS and AVHRR [9] do not meet these requirements, information about the main remote sensing systems is given in table 1.

At the moment, images from the ETM + [10] have the highest resolution and are best suited for studying the internal thermal structure of cities, but since 2003, the ETM+ radiometer provides data with irreplaceable defects.

In turn, the ASTER system has a comparable spatial and much higher spectral resolution, [11], but after 2018, data from this device is received with very low frequency. From the above facts, it can be concluded that at the beginning of 2020, it is advisable to use data from the following systems for
obtaining surface temperature maps on a city scale: ETM+ before 2003; TIRS since 2013; ASTER –
for availability as additional data.

Table 1. Information about remote sensing systems in the thermal range of the Earth.

| Name   | KA system      | Country | The time of operation, years | Spatial resolution, m |
|--------|----------------|---------|-----------------------------|----------------------|
| ETM+   | Landsat-7      | USA     | 1999 to present.            | 60                   |
| ASTER  | Terra          | USA     | 1999 to present.            | 90                   |
| TIRS   | TIRS Landsat-8 | USA     | 2013 to present.            | 100                  |
| MODIS  | Terra, Aqua    | USA     | 1999 to present.            | 1000                 |
| MSU-MP | Meteor-M No. 1 | Russia  | 2009 to present.            | 1000                 |

The official USGS geological portal is the most convenient source for searching and uploading images from various systems since this portal has the most convenient image search system for all the listed systems with the ability to filter results by cloud level.

This paper uses data from the ETM+ sensor of Landsat 7 for August 2002 and the TIRS sensor of Landsat 8 for data for August 2019. All satellite images from Landsat 7 and 8 systems are provided as digital values from the sensor (Digital Number, DN) in a pre-adjusted form for the visible range, namely, with radiometric and geometric correction. To obtain information from the thermal channels required for the compilation of a PGS heat map or the so-called LST (land surface temperature) map, are usually required [12]. Currently images from Landsat 7-8 systems are distributed on the Earth Explorer portal in an already processed form, fully suitable for operation in the visible range, while only atmospheric correction for the desired channels is required. At the same time, there are data sets with atmospheric correction performed, without a thermal channel, which is not suitable for solving our problem.

Atmospheric correction of images is the process of reducing the influence of the atmosphere on the image by correcting the values on the device's sensor, taking into account the passage of the signal through the layers of the atmosphere. To perform a full-fledged atmospheric correction of thermal images, additional information about the state of the surface and atmosphere at the time of shooting is required. However, there are several ways to perform atmospheric correction that do not require additional information. For example, the dark Object Subtraction method (Dark Object Subtraction, DOS) [13]. However, currently researchers do not stop discussing the need for atmospheric correction of images, since there is still no reliable way to determine the amount of moisture in the atmosphere, so in this case it is advisable to consider the least time-consuming automatic methods.

2.1. Methods for obtaining satellite images

After getting the necessary images and performing atmospheric correction, you can proceed to direct processing of images to obtain an LST-map. There are several approaches to converting the initial numerical values of image brightness DN to surface brightness temperatures in degrees Kelvin and Celsius. If we generalize the main steps of image transformations for Landsat8[14], we can get the following algorithm for switching from the values on the DN sensor to the values of the LST(figure 1):

\[
LST = TB \cdot \left(1 + \lambda \cdot TB / c_2 \cdot \ln(\text{emissivity})\right)^{-1}
\]

where: \(\lambda\) = wavelength of emitted radiance; \(c_2 = h \cdot c / s = 14388\ \mu m\ K\); \(h\) – Planck’s constant; \(c\) – velocity of light; emissivity – surface emission; \(TB\) – At-Satellite Brightness Temperature (K).

As can be seen from the diagram of the algorithm, to calculate the values of LST by formula 1, it is also necessary to calculate the reflectivity parameter of the earth's surface[15]. There are several different ways to account for this parameter, for example, on the basis of NDVI [16] or by classifying the earth's surface by macro classes, it is also possible to use constants in the case of a homogeneous
Existing studies [17] note a fairly high convergence of the obtained temperature data for emissivity calculation methods, based on the NDVI parameter or surface classification, the final choice of the method depends on the problem being solved and its scale. In this study, a method based on supervised semi-automatic classification was chosen, due to its simplicity, clarity, and more precise control of the result.

![Figure 1](image)

**Figure 1.** Block diagram of the satellite image processing algorithm, a) General scheme for calculating LST b) algorithm for calculating LST for Landsat 8.

Thus, conducting atmospheric correction of images and taking into account the radiative capacity of the earth's surface (emissivity) are the main factors determining the variety of methods for calculating LST. In this paper, we have considered the simplest method of image processing, which allows us to achieve maximum automation.

The QGIS software package with a plug-in extension Semi-Automatic Classification Plugin (SCP) was used as a tool for automating image processing and performing raster operations [18]. This extension allows you to automate a significant part of the process of processing satellite images and perform all the necessary corrections, as well as calculate the emissivity coefficient by signature classification using samples [19]. As the initial data for the experiment, we selected a pair of images of the city during the summer period for 2002 and 2019, to record changes in the distribution and the heat island effect over the city over time.

3. Results and analysis

To analyze the nature of the distribution of thermal anomalies, as well as to increase the visibility and ease of localization of anomalies, the resulting rasters were combined with the image of the city map in the - multiplication overlay mode. The resulting images were analyzed for strong differences in the distribution of figure 2.

The obtained LST maps in absolute values are certainly far from the stated 0.1-1 degrees of the sensor's sensitivity, so these data should be considered as a qualitative picture of the distribution, focusing on visual changes in the General distribution of warm areas on the territory of the city. For example, if there are general temperature maxima in the zones of industrial enterprises and urban landfills, we can note a more blurred gradient of heat spots for later images, as well as a general expansion of the urban heat island zone to the West, following the urbanization of territories of the
city towards previously green areas. Thus, these observations confirm the conclusion that the process of urbanization and compaction of buildings, accompanied by an increase in the number of cars and asphalt surfaces, inevitably leads to an increase in the overall average temperature in the vicinity of the city center. Also, we can see appearance of new temperature peaks and anomalies that contour with the zones of new development.

An interesting result can be the analysis of 6th and 7th channels of the TIRS sensor, these channels cover part of the near infrared radiation spectrum (NIR and SWIR)[20], and may carry additional hidden information about powerful thermal radiation sources. At the same time, these channels have a high contrast and spatial resolution about 30 meters per pixel. These results are well illustrated in figure 3, where clearly visible heat sources are observed. In this drawing, the main heat sources are highlighted by the active emission of smoke and steam from operating power plants. At the same time, additional bright spots of small size that are not visible on the color composite can be seen on the infrared channel of the image after the histogram equalization procedure [21].

![Figure 2](image-url)

**Figure 2.** (LST) for Chelyabinsk: a) for August 2002 and b) for August 2019.

![Figure 3](image-url)

**Figure 3.** Image of Chelyabinsk in the thermal range (Band6) a) with overlay in multiplication mode on the color composite b) band6 after histogram equalization.

4. Conclusions and discussion
As a result of the analysis of the obtained images it is possible to conclude that these thermal bands of Landsat 8 is suitable for the study of urban heat Islands at the level of the neighborhoods of the city. Based on the obtained images for Chelyabinsk, we can note a marked change in the distribution of thermal anomalies and high temperature zones due to changes in the nature of development and expansion of agglomeration associated with the process of urbanization and the replacement of green cover with residential buildings.

The result of this article is a brief description of simple methods for automated acquisition and processing of satellite thermal images of the surface of the urban environment. The described tools and
methods allow you to automate the acquisition of a large amount of data on seasonal and long-term changes in the temperature of the earth's surface in and around the city. It was found that an additional detailed study of band 6 images from the TIRS sensor after initial processing and bringing to the surface reflectance allows you to identify sources of strong infrared radiation hidden from the observer in the visible range and on the LST map, due to its lower resolution (100 m vs. 30).

The results and methods obtained in this work can be useful for solving applied problems of urban planning, as well as in problems of urban climatology and ecology. Further development of this work may be the study of the applicability of the data obtained for localization of environmental violations and eco-monitoring of territories, by analyzing night images in the near-infrared range, which will allow identifying sources of unauthorized emissions to the atmosphere by thermal traces with high accuracy.

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