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Mapping Urban Heat Islands of Arctic Cities Using Combined Data on Field Measurements and Satellite Images Based on the Example of the City of Apatity (Murmansk Oblast)

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Abstract—This article presents the results of a study of the urban heat island (UHI) in the city of Apatity during winter that were obtained according to the data of field meteorological measurements and satellite images. Calculations of the surface layer temperature have been made based on the surface temperature data obtained from satellite images. The experimental data on air temperature were obtained as a result of expeditionary meteorological observations, and the experimental data on surface temperature were obtained based on the data of the space hyperspectral Moderate-Resolution Imaging Spectroradiometer (MODIS) system, channels 31 and 32 (10.78–11.28 and 11.77–12.27 micrometers, respectively). As a result of the analysis of temperature fields, an intensive heat island (up to 3.2°C) has been identified that was estimated based on the underlying surface temperature, and its mean intensity over the observation period significantly exceeds the representative data for European cities in winter. It has also been established that the air temperature calculated according to the MODIS data is systematically higher under winter conditions than the air temperature from direct measurement data.

Keywords: urban heat island, Apatity, field meteorological measurements, thermal satellite images, microclimatology, MODIS

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INTRODUCTION

In recent decades one can note stable growth in the scientific and social interest for the climatic pattern of megalopolises, in particular, for urban heat islands (UHIs). This is easily explained by the fact that the correct understanding of this climatic phenomenon can seriously save municipal budget funds through reduced costs on heating in winter. In southern regions the economic effect is expressed in the reduction of energy consumption for housing premises conditioning in summer.

The main attention of specialists in the area of urban meteorology is currently focused on megalopolises in areas with warm climate, which is associated with the significant prevalence of large cities in these regions.

Meanwhile, there is much less information on the microclimatic pattern of cities located on the other side of the temperate zone, i.e., beyond the polar circle. There are only single studies that were conducted in Alaska and showed the existence of heat islands in winter in the relatively small cities of Barrow and Fairbanks. Thus, despite the relatively small population (35000 people) and low-rise housing traditional for the United States, the temperature in winter months is, on average, more than 1° higher in the center of Fairbanks than that in the airport situated beyond the city (Magee et al., 1999). It can be expected that this effect will be significantly stronger in larger cities with a more dense development. The study of polar heat islands also has an important ecological aspect: under the polar night conditions, with the absence of solar radiation, they are largely formed by anthropogenic heat sources, and their study will make it possible to obtain data on the thermal environmental pollution.

However, a study of the UHI effect according to the data of direct meteorological measurements in the subarctic zone (which is generally occupied by the Russian cities) is almost impossible, since there are very few meteorological stations here. Therefore, satellite data and specialized expeditionary campaigns are of particular interest.

The objective of this work is to study the prospects of remote sensing of urban heat islands in polar latitudes based on the example of the Russian city of Apatity (Murmansk oblast). It significantly surpasses Barrow and Fairbanks in area and population. At the same time, its lowland position, which does not allow inversions to influence the temperature conditions of the urban area, and high development density, as well as low winter temperatures determining high energy

Fig. 1. Automatic meteorological station (AMS) Davis Vantage Pro 2 (on the left), iButton thermal sensors (in the center), and an example of their setup in the course of study (on right).

demands for heating, make it one of the best sites for studying the effect of heat islands in polar cities.

This work compares experimental data on the thermal urban structure in winter with the surface-temperature data obtained from satellite images in the thermal infrared (IR) range (thermal satellite images). The subsatellite experiment was carried out in the area of the city of Apatity in 2014 from January 26 to February 4.

The images of the MODIS multichannel spectroradiometer (Moderate-Resolution Imaging Spectroradiometer) are a valuable material for studying urban heat islands, although their application in this area is limited. These devices are installed in the NASA's EOS–Terra and Aqua satellites. Both satellites are located on circular subpolar sun synchronous orbits with a height of 705 km, and their operation is coordinated so that they could receive comparable data. The Terra satellite was launched December 18, 1998, and the Aqua satellite was launched later on May 4, 2002.

The hyperspectral MODIS system performs a survey in 36 channels in the visible, near, mid, and thermal IR spectra. We are interested in the data of channels 31 and 32 (10.78–11.28 and 11.77–12.27 μm, respectively), in which the intensity of the Earth's surface thermal emission is recorded and which cover the range corresponding to the maximum intrinsic emission of the Earth (10–12 μm).

The spatial resolution of images received in these channels is 1000 m.

The MODIS system performs a survey in several channels in the thermal IR spectrum which makes it possible to recover the Earth's surface temperature to a high accuracy according to the transparent split-window algorithm. For this reason, MODIS images are used to assess the accuracy of algorithms for recovering the Earth's surface temperature from images made by other devices, e.g., TM and ETM+ (Li et al., 2004). For our task, an important advantage is the large spatial coverage of these images, which makes it possible to assess the size of large heat islands and compare heat islands of different cities with each other (Hung et al., 2006; Cheval et al., 2009; and Imhoff et al., 2010). However, despite these advantages, MODIS system images are characterized by a significant drawback that is especially visible when investigating heat islands of small towns (such as Apatity), namely, a low spatial resolution. Unlike images with a higher spatial resolution, such as images of TM, ETM+, ASTER, or TIRS systems, it is more difficult to identify the internal heat-island structure according to MODIS system images. The application of definitely MODIS system images in this work is explained by the absence of images with a higher resolution for the area under investigation over the field observation period. However, in our case, the use of MODIS system images has reasonably proved their value.

RESEARCH METHODS

The following two types of instruments were used to obtain direct data on the thermal structure of the surface air during field measurements at an altitude of 2 m within the city of Apatity:

(1) Davis Vantage Pro 2 automatic weather stations (AWSs) (Fig. 1, on the left) that measure temperature, humidity, pressure, and wind velocity and direction and have been proven well in domestic studies due to their relatively low cost, reliability, and high accuracy of air temperature measurements (0.5°C);

(2) iButton thermal sensors from the Maxim Integrated company (http://www.maximintegrated.com/), which represent an air-temperature measuring instrument and data logger (to an accuracy of 0.5°C) in a metal casing with a small size (Fig. 1, on the center and right).

The iButton thermal sensors were installed in a relatively uniform way throughout the city and its suburbs at a standard measurement level of 2 m (Fig. 1, on the right). The layout of measuring instruments is shown in Fig. 2. The background AWS that is not marked on the map was installed to the west of the city on the shore of Lake Imandra.

The instruments installed in the course of expedition operated from January 28 to February 3, 2014 in the city of Apatity, and the measurement frequency was 10 min.

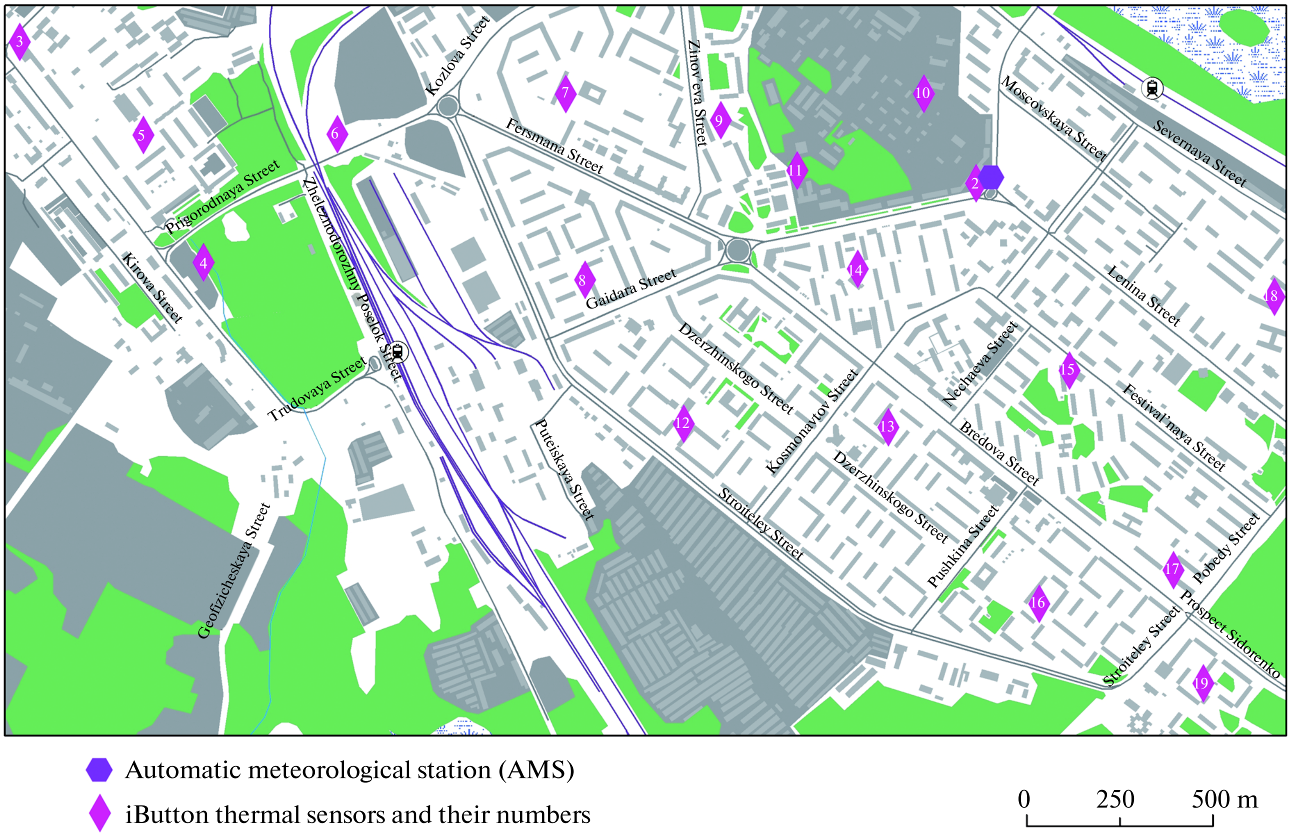

Fig. 2. Sensors and AMS location in the area of the city of Apatity.

Information on the Earth's surface temperature was received from thermal satellite images of the MODIS system. This work used a product containing data on the Earth's surface temperature calculated by values of the intensity of thermal emission and atmospheric parameters: MOD10A1 (based on the Terra satellite data) and MYD10A1 (based on the Aqua satellite data), data collection 5 (the most up-to-date data version at the present time). The MOD10A1 and MYD10A1 products are distributed free in the *.hdf format through the EOSDIS system (NASA's Earth Observing System Data and Information System). The MOD10A1 and MYD10A1 products include several data layers presented in the sinusoidal projection. To obtain a clear picture of the Earth's surface temperature distribution, it is necessary to perform a geometric transformation of layers, convert them into a conveniently processible format, and obtain the Earth's surface temperature values in Celsius.

The measurement of projection of data and their conversion to other bitmapped formats are made using the MRT software (MODIS Re-projection Tool) distributed free for registered EOSDIS users. The layers were converted to the UTM projection, zone no. 36, bitmapped format *.tiff.

The data on the Earth's surface temperature are included in the LST_Day_1km and LST_Night_1km layers. To convert them to Kelvin, it is necessary to recalculate the values of all layer pixels according to formula

$$\mathrm{LST} = 0.02R, \tag{1}$$

where LST is the value of the surface temperature in kelvins and R is the initial values of pixel brightness.

Information on the time of registration pixels covered by the area of the city of Apatity was received from the Day_view_time and Night_view_time layers. The following relation was used to calculate temperature in the surface air, based on the air temperature (Niclos et al., 2014)

$$\mathrm{SAT} = 0.94\mathrm{LST} + 19.3, \tag{2}$$

where SAT is the temperature of the atmospheric surface layer in kelvins and LST is the Earth's surface temperature in kelvins.

There are several variants of the relation between the Earth's surface temperature obtained from satellite data and the air temperature in the atmospheric surface layer, these relations being separately distinguished for day and night data. Relation (2) was obtained for night conditions in the east of Spain. The mean square error of this relation is estimated to be 1.69°C. If we compare the results of a calculation of the surface layer air temperature according to this for-

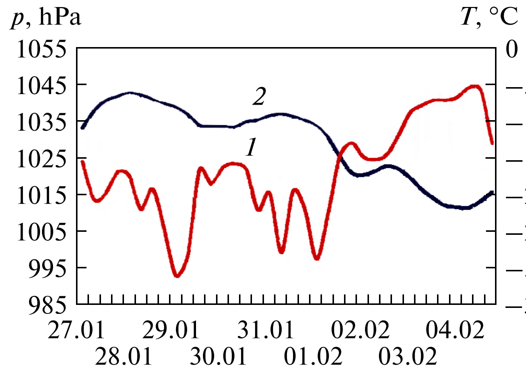

Fig. 3. Variation of air temperature at an altitude of 2 m and of pressure at sea level during the experiment (according to the data of the meteorological station of the city of Almaty, Murmansk Hydrometeorological Service Management).

mula with calculations according to other more complex formulas given in (Niclos et al., 2014), we find that relation (2) is quite comparable with others in terms of accuracy. Therefore, for the sake of calculation simplicity, the authors decided in favor of this particular relation.

Calculations were also made with respect to an analogical relation for day conditions. The results were unsatisfactory, which seems to be due to the prevalence of stable stratification in the winter atmospheric boundary layer in polar regions, which is also characteristic of the night boundary layer of temperate latitudes.

When analyzing data, we proceed from the assumption that small smooth topographic differences (up to 20 m in the central part) should not have a significant influence on the temperature field of the area under consideration.

RESULTS AND DISCUSSIONS

The analysis of synoptic processes combined with the analysis of data of observations during the expedition has made it possible to distinguish two synoptic periods (Fig. 3). During the first period (January 26–February 1), the Kola Peninsula was at the periphery of a powerful (up to the level of 500 hPa) blocking anticyclone (Fig. 4a), which covered a vast area including Eastern Europe, the entire European part of Russia, and western and eastern Siberia (Fig. 4b). The high atmospheric pressure (1035–1045 hPa) persisted during the entire period. A frosty calm and largely clear weather with an insignificant amount of subinversive cloudiness was observed in the second half of the period.

There was an intensive radiative cooling under the conditions of clear anticyclonic weather, and a temperature minimum was recorded in this period over the entire period of our observations: according to the AWS data, the temperature dropped to −22.6°C in the center of the city of Apatity (−27.4°C in the suburb) at night from January 31 to February 1. During the first synoptic period, inversions with a capacity reaching 18–20°C/1.5 km were observed (Fig. 5). Because of the best cloud conditions, it was this synoptic period that was chosen for further analysis. The continental nature of the air mass prevailing in the first period is evidenced by a low integral moisture content in the air column (up to 2.6 kg/m^2).

Among all considered satellite images, a 6 × 8 km area covering the central part of the city was separated. After separating the area of interest, images were chosen with a number and position being adequate for

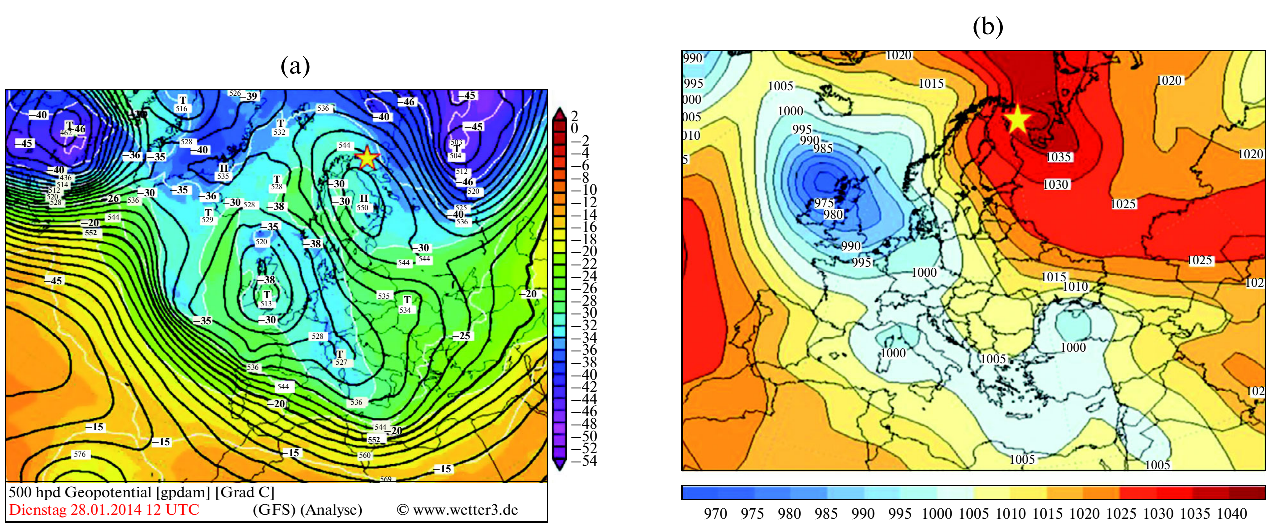

Fig. 4. (a) Geopotential altitude (isolines) and temperature (color) on the surface, 500 hPa 28.01.2014 12 UTC (http://www.wetterzentrale.de); (b) pressure at sea level, 27.01.2014 12 UTC (according to the data of NCEP/NCAR reanalysis).

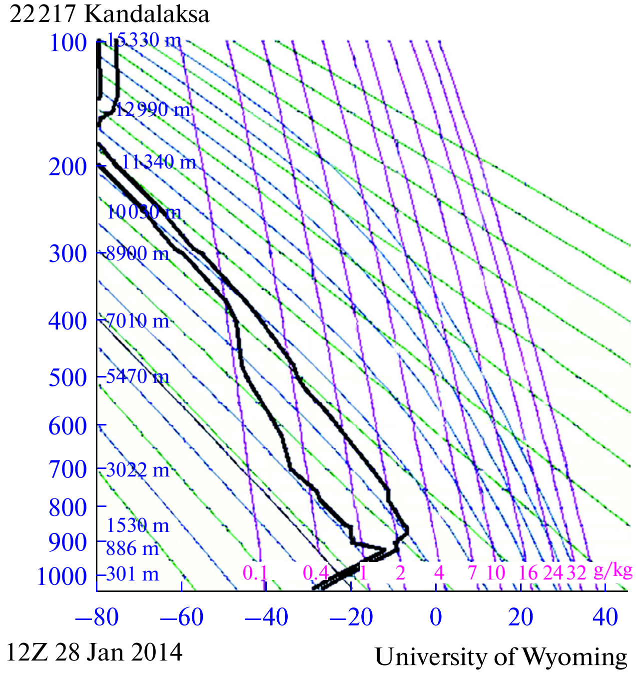

Fig. 5. Aerological diagram 28.01.2014 12 UTC (aerological station in the city of Kandalaksha, http://weather.uwyo.edu).

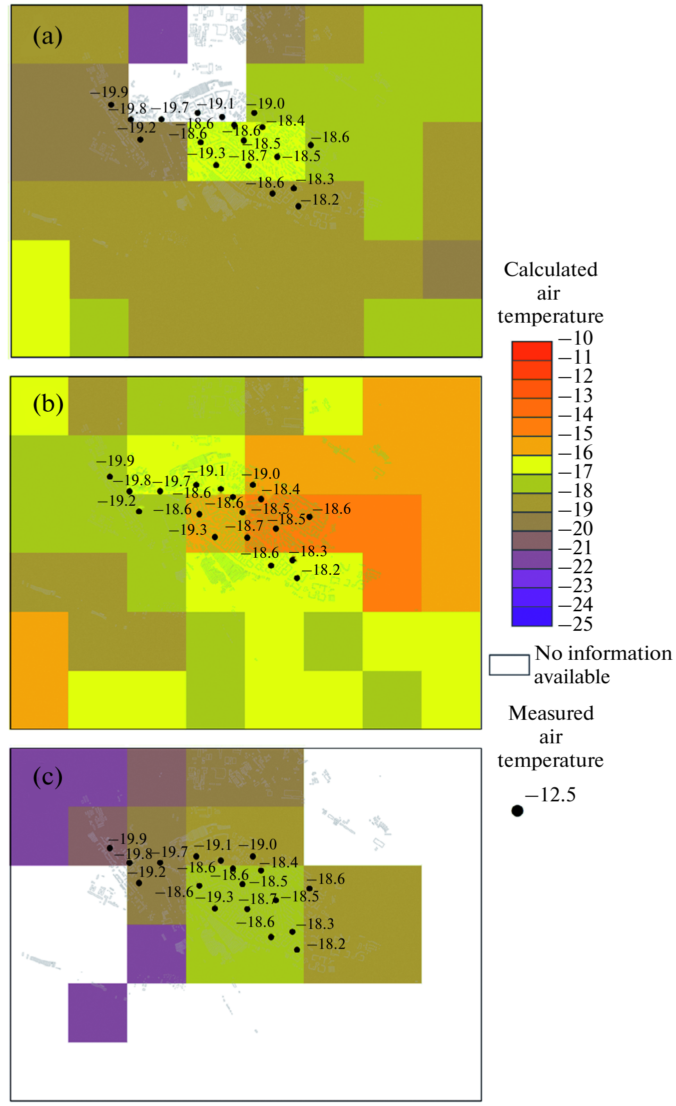

Fig. 6. Comparison of air temperatures obtained according to the results of direct measurements and calculated according to the data of satellite images of the MODIS system: (a) January 29, 23:40; (b) January 30, 03:40; (c) January 31, 02:40 (Moscow time).

studying the urban heat island and its relationship with the heat island identified according to the measurements of surface air temperature: images for January 29, 23:40; January 30, 03:40; and January 31, 02:40 (Moscow time).

Figure 6 and Table 1 present the mutual ratio of air temperature calculated according to the MODIS data and air temperature calculated according to the data of the installed iButton sensor network. Table 2 compares the values of SUHI (the Surface Urban Heat Island and UHI).

As can be seen from Table 1, the spatial amplitude of the calculated values of the heat island according to the satellite data is, on average, 2.7°C, while the air-temperature amplitude within the city, i.e., the urban heat island (UHI), is only 1.6°C. A systematic overestimation of absolute air temperatures according to the MODIS data is also particularly noticeable (the closer the area is to the center of the city, the higher the temperature is). Since it is difficult to perform accurate measurements of the underlying surface temperature so that they could be synchronous in time with satellite data, one has to analyze only differences between UHIs that were obtained by different methods. The surface temperature is steadily lower than the air temperature, which is quite natural for nighttime and temperature-inversion conditions.

The data on the heat island (UHI) and the direct data on the surface heat island (SUHI) (Table 2) correlate well to each other; however, the spatial range of the latter is almost 3–4 times larger than the mean value for European cities (1.7 ± 0.4° during the day and 0.4 ± 0.4 at night, according to the data of Peng et al. (2011)). This can be explained by the specificity of cities situated beyond the polar circle. The average daily difference, which constitutes several degrees, between the air temperature averaged over all points and the underlying surface temperature averaged over all MODIS pixels appears to be quite reasonable in terms of classical microclimatology. The underlying surface is colder than air, which is associated with the stable stratification of the atmospheric surface layer that was recorded during the expeditionary observations.

Table 1. Air temperature established from MODIS data, and data of direct measurements of air temperature using iButton sensors

Date and time	Data	Mean value within the city limits, °C	Range of values (heat island capacity), °C	In the central part of the city, °C
January 29, 23:40	MODIS	–17.1	2.7	–15.7
	iButton direct measurement data	–17.8	1.9	–17.6
	ΔT, °C	0.7		1.9
January 30, 03:40	MODIS data	–15.3	3.2	–14.9
	iButton direct measurement data	–16.2	1.1	–16.2
	ΔT, °C	0.9		1.3
January 31, 02:40	MODIS data	–17.4	2.3	–16.6
	iButton direct measurement data	–18.9	1.7	–18.7
	ΔT, °C	1.5		2.1
Mean value	MODIS data	–16.6	2.7	–15.7
	iButton direct measurement data	–17.6	1.6	–17.5
	ΔT, °C	1.0		1.8

Table 2. Comparison of period average data on air temperature and underlying surface that were established from the MODIS data with the data of direct measurements of air temperature using iButton sensors

Temperature	Mean value within the city limits, °C	Range of values (heat island capacity), °C	In the central part of the city, °C
Air temperature, MODIS	–16.6	2.7	–15.7
Surface temperature (asphalt, soil, and snow), MODIS	–22.00	4.4	–19.9
iButton direct measurement data	–17.6	1.6	–17.5

CONCLUSIONS

According to the results of the conducted study, we can make the following conclusions:

(1) All the applied thermal satellite images show the existence of both the surface heat island (SUHI) in the area of the dense development of Apatity that is surrounded by Fersmana, Stroiteley, Pobedy, and Severnaya streets, and the classical heat island (UHI). Differences in the surface temperature between the specified area and the surrounding area reach 4–5°C.

(2) For the night period in winter, the remote sensing data on air temperature in Apatity are satisfactorily correlated with the data on direct measurements using thermal sensors. The error does not exceed the methodic error described in (Niclos et al., 2014), but the absolute temperature values are, on average, one degree overestimated.

The surface heat island (SUHI) and the classical urban heat island (UHI) were synchronously assessed for the city situated beyond the polar circle for the first time. The data obtained by us do not always coincide with the conclusions of the previous authors on the intensity of the surface heat island in European cities for the winter period, which seems to be due to the location of the city of Apatity beyond the polar circle.

An issue on the relation of the values of surface temperature and air temperature under Apatity conditions was also considered. According to the MODIS data, the intensity of the heat island (UHI) exceeds the analogical one according to the direct measurement data by 1°C, on average. However, for the conditions of high vertical temperature inversions, the surface is, on average, steadily colder (by 4–5°C within the entire city), which corresponds to the theoretical concepts.

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