Application of the landscape approach and remote sensing data for the mapping of the climate characteristics of the mountain-basin territories

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Abstract. Air temperature is one of the most important climate characteristics, which is used for climate research, investigation and modeling of vegetation, hydrological parameters and other landscape components as well as geosystems entirely. The use of a landscape approach greatly simplifies the process of visualizing meteorological parameters and allows you to take into account influencing factors, since they have already been taken into account when drawing up a landscape map. This article describes cartographic models of the air temperature field of the Tunka intermountain basin created using in-situ wide network of modern automatic measuring instruments and remote sensing methods that allow us to solve the problem of climate research at a local level, as well as a landscape-interpretation mapping method. The main advantages and disadvantages of these cartographic methods are assessed. It is shown that a joint analysis of the data from a dense network of field observations, remote sensing data, and a landscape map made it possible to analyze the dynamics of the spatiotemporal distribution of the air temperature field with a relatively high degree of accuracy.

1. Introduction
The climatic changes of the last decades have reached considerable pace and scale. Changes in the climate system are caused by many natural and anthropogenic factors, have a complex spatio-temporal structure and are observed in a wide range of meteorological elements. The ongoing climate changes, with different focus and degree of intensity, affect the transformation of existing natural-territorial complexes. As a result, monitoring of climate characteristics and an objective assessment of their dynamics are an important part of solving the problems of effective environmental management and sustainable development of territories.

A fundamentally important step in monitoring climate characteristics and generalization data obtained for individual observation points is the construction of maps. The cartographic material, which is highly informative and has a visualization of the continuous distribution of meteorological parameters, allows us to analyze the patterns of the territorial distribution of meteorological elements and its deviations from the norm. In addition, climate maps can be predictive.

Isolinear method for mapping of meteorological elements is commonly used - the values of the element being mapped at the observation points are plotted to the gypsometric basis, then, taking into account general climatic and geographical patterns, isolines are drawn using interpolation. With a simple structure of the earth's surface and the presence of a dense network of observations, this approach is very convenient, has high information content and accuracy of the cartographic material.
However, for a territory with a complex relief (the presence of mountain-hollow landscapes) and insufficient illumination with primary meteorological information, mapping using isolines is a rather difficult task [1, 2].

In particular, the distribution of air temperature under rugged terrain is greatly influenced by the orographic features of the area, such as: the place’s protection from the main air currents, altitude, orientation of the slope, and underlying surface conditions. With the combination of many variations of natural conditions in the mountains, as well as with complex fluctuations in relative heights and exposures, a special regime of air temperature develops. So, convex surfaces (the top of the slope) contribute to a decrease in amplitude, and concave relief elements (valley or hollow) increase it. As a result, the course of gradients between different relief forms can be quite sharp and anomalously large. Thus, for monitoring and mapping of climatic characteristics in the conditions of mountain-hollow landscapes, a good knowledge of the physical and geographical features of the territory, as well as the patterns of distribution of meteorological elements in various relief forms, is required.

In addition, the extreme shortage of primary weather information has a significant effect on the representativeness of the resulting cartographic material. Thus, when monitoring and mapping the climate of hard-to-reach areas with difficult climatic conditions, it is advisable to use data from additional monitoring systems and alternative methods for visualizing meteorological parameters.

This article describes cartographic models of the air temperature field using the example of the Tunka intermountain basin created using various alternative methods, and their main advantages and disadvantages are assessed. As alternative methods for monitoring and extrapolating point characteristics data, we use data from a wide network of field observations using modern automatic measuring instruments and remote sensing methods that allow us to solve the problem of climate research at a local level, as well as a landscape-interpretation mapping method [3, 4].

2. Objects, data and methods

The Tunka intermountain hollow is located in the southwestern part of the Baikal region. The hollow is located at the junction of the Tunkinsky Goltsy and Khamar-Daban ridges, belongs to the zone of island distribution of permafrost strata and is characterized by a high continental climate. Due to the significant natural differences between the central part of the basin and its mountainous framing, the study area is characterized by a variety of landscape conditions, landforms and parent rocks, as well as a long history of economic development [5]. All this allows us to study the features of the temperature regime of various mountain-hollow landscapes (from goltsy and mountain taiga to steppe) on a compact territory.

Since 2007 in Tunka hollow, the semi-stationary complex landscape, including climatic studies are carried out. A database of the study area was created, containing topographic maps, a digital elevation model (SRTM), Landsat 5, 7, SPOT 4 multi-temporal satellite images, as well as existing small-scale geological and landscape maps of the territory. In previous studies, the authors validated Landsat remote sensing data in the thermal range based on ground-based observations using thermochron sensors; based on these satellite images, the spatiotemporal dynamics of the temperature field of the studied area was analyzed. Temperature inversions and their characteristics were analyzed [3, 6].

To obtain a detailed spatio-temporal picture of the distribution of surface air temperature in the study area, electronic thermographs are used, which allow solving the problems of climate research at a local level. Thermographs are a fully protected two-channel electronic recorder that accumulates in its own volatile memory the temperature values of the environment surrounding it, with reference to real time. At present, there are about 37 observation sites on the territory at heights from 806 m to 2119 m. The sensors are installed in such a way that they form a profile from the right to the left side of the basin and cover the area of each landscape section represented on the territory. Thermographs are programmed for measurements with a frequency of collecting readings every 3 hours, synchronously with measurements at weather stations and installed at a height of 2 m above the surface of the soil. Thermographs are widely used in modern scientific research. The ability to measure temperature in various environments, storing a significant amount of information, the
function of recording data with different frequencies and small dimensions allow the successful use of electronic thermographs for many tasks of modern science [7-9].

Mapping of the air temperature field using the first method is made based on a landscape-typological map of the territory at the level of facies classes M 1: 200000 [10]. The study area is represented by nine classes of facies, belonging to four groups of geomes: Tunka Goltsy ridge: 1 – Class of goltsy facies; 2 – Class of mountain taiga (pine–larch with Siberian pine) facies on steep slopes; 3 – Class of mountain taiga (Siberian pine–larch and pine); 4 – Class of psammomorphic pine forests; 5 – Class of cryohydromorphic meadow lake wetland facies; 6 – Class of meadow-steppe facies of the Irkut valley; 7 – Class of anthropogenic facies (steppe-meadow); Khamar-Daban ridge: 8 – Class of mountain taiga (larch with Siberian pine) facies on smooth slopes; 6 - Class of mountain taiga (larch with Siberian pine and dwarf birch) facies on flat interfluve.

The method of landscape-interpretation mapping of the characteristics of the temperature field is used in the work [4]. The method is based on the fact that a certain type of landscape (for example, a group of facies) has homogeneous natural characteristics throughout its range. This allows extrapolating the characteristics (including air temperature) measured at one or several points of the range of a certain group of facies over the entire area of the range.

Also, when mapping meteorological parameters in difficult orographic conditions and with a limited network of meteorological stations, it is advisable to use remote sensing methods [11, 12]. Methods for remote determination of surface temperature from satellite data are widely developed and allow, with varying degrees of accuracy, to visualize the continuous distribution of the temperature field. A satellite radiometric camera takes pictures in the infrared range and displays the radiation temperature averaged over the pixel of the image and the spectral range of radiometric measurements [13]. The outgoing radiation detected by the camera depends on the thermodynamic temperature of the surface and its emissivity. In most cases, when converting the brightness characteristics of images in the thermal range to temperature values, the emissivity of objects is not taken into account, which leads to significant distortions and inaccuracies. This is especially true for mountainous areas with a high variety of underlying surface types, since the emissivity of different types of landscapes (open land, sand, steppe, various types of forests, etc.) has differences. All this greatly affects the accuracy of the resulting cartographic material. As a result, it becomes necessary to assess the correctness of using remote sensing data to map the temperature field.

To analyze and mapping the spatial distribution of the temperature field using remote sensing method, satellite images of Landsat 5 and Landsat 7 for the period 2010–2012 were used for the following dates (the number of Landsat satellite is in brackets - 5 or 7), which corresponds to the filming systems “thematic mapper” (TM) and “improved thematic mapper plus” (ETM +): 01/16/2010 (5), 02/09/2010 (7), 02/25/2010 (7), 04/30/2010 (7), 06/01/2010 (7), 07/03/2010 (7), 07/11/2010 (5), 07/19/2010 (7), 07/27/2010 (5), 09/29/2010 (5), 11/24/2010 (7), 04/01/2011 (7), 07/14/2011 (5), 09/08/2011 (7), 10/02/2011 (5), 11/27/2011 (7) 03/18/2012 (7), 06/22/2012 (7), 08/09/2012 (7), 08/25/2012 (7), 11/29/2012 (7), 02/01/2012 (7), 03/21/2012 (7), 05/05/2012 (7). The spatial resolution of the far infrared band of these images (channel 6) is 120 and 60 m for the Landsat 5 and Landsat 7 satellites, respectively. The images were downloaded from the server of the Center for Earth Resources Science and Research of the US Geological Survey (EROS USGS USA) and pre-processed using the calibration algorithm embedded in the ENVI software (http:// glovis.usgs.gov/). For a temperature band, the algorithm translates the DN (Digital Number, brightness of the original image) into temperature values without taking into account the emissivity of landscapes. Atmospheric image correction was performed using the FLAASH module (Fast Line of Sight Atmospheric Analysis of Spectral Hypercubes) for the ENVI software.

Validation of satellite images was made by comparing Landsat temperature data and a dense network of point field measurements. It is shown that the dependences of the temperature displayed on the images and the air temperature on the sensors are complex, have landscape and seasonal specifics, seasonal trends persist from year to year. Also, deviations of the temperature measured by remote and ground-based methods are associated with a difference in surface and air temperatures at a height of 2
m, a difference in the spatial scale of measurements (a point for ground-based measurements and a pixel for an image), and also with the influence of the emissivity of landscapes on remote measurements. The arithmetic average of deviations for all points and moments of shooting 3°C; minimum deviations (1-3°C) correspond to autumn, winter and early spring, maximum (3-5.5°C) to the period from April to September, Landsat temperature values are overestimated for open areas and underestimated for forest landscapes [6].

3. Results and discussion

According to the measurements at the observation sites located within the boundaries of the sections of each type of landscape of the Tunkinsky basin, the average monthly air temperature values for each month of 2013 are calculated (table 1). The obtained values were extrapolated to the entire area of the landscape allotment. The results are presented in the form of maps of the spatial temperature distribution (figure 1) [14].

Table 1. Average monthly air temperature within different classes of facies of the Tunka depression

| Classes of facies | Range of altitudes, m | N\textsuperscript{a} | Average monthly air temperature °C, |  |
|------------------|----------------------|----------|-----------------|-----|
|                  |                      |          | January         | July|
| 1                | 1450-2900            | 2        | −15.7           | 9.6 |
| 2                | 1050-2500            | 4        | −14.3           | 13.9|
| 3                | 800-1600             | 6        | −19.4           | 15.7|
| 4                | 750-900              | 4        | −25.5           | 17.2|
| 5                | 700-850              | 10       | −27.6           | 17  |
| 6                | 600-800              | 4        | −24.8           | 16.9|
| 7                | 700-1000             | 3        | −22.7           | 16.8|
| 8                | 750-1600             | 3        | −16.7           | 15.3|
| 9                | 800-1850             | 2        | −15.7           | 14.7|

\textsuperscript{a}Note: number of sensors

The reliability of the cartographic material is confirmed by a linear relationship and high correlation coefficients (0.98) between measurements of air temperature for all observation sites and the average monthly values reflected on the maps. The average module of air temperature deviations calculated according to the measurement data and displayed on the maps for all sites and months is 0.3°C. During the year, the error value varies from -1.3°C to 1.3°C, does not depend on the season and, accordingly, on the temperature value. The difference between the measured average monthly temperatures at individual sites and the temperature fields presented on the map during the year in 96.5% of cases does not exceed ± 1 °C, and in 87% of cases ± 0.5°C.

To map the air temperature field on the basis of satellite data, images were used, the average module of which deviations from field observations does not exceed 3°C. Temperature maps with a step of 5 °C were constructed from the selected images (figure 2).

As a result of the analysis of the obtained cartographic material, the features of the temperature regime of landscapes of the Tunkinsky intermountain basin located in various relief forms were established. A difference is noted between the characteristics of the temperature regime of landscapes in the bottom of the basin and on its slopes during the cold and warm periods. The values of air temperature gradients on the slopes of the Khamar-Daban and Tunkinsky Goltsy ridges were calculated, the presence of year-round temperature inversion on the slopes of different exposures was noted, and its characteristics were described.
Figure 1. The spatial distribution of the average monthly air temperature (°C) within different types of landscapes of the Tunkinskaya basin. 
a – in January: 1 – -27 ÷ -28, 2 – -26 ÷ -27, 3 – -25 ÷ -26, 4 – -24 ÷ -25, 5 – -23 ÷ -24, 6 – -22 ÷ -23, 7 – -21 ÷ -22, 8 – -20 ÷ -21, 9 – -19 ÷ -20, 10 – -18 ÷ -19, 11 – -17 ÷ -18, 12 – -16 ÷ -17, 13 – -15 ÷ -16, 14 – -14 ÷ -15; b – in July: 1 – 17–18, 2 – 16–17, 3 – 15–14, 4 – 14–15, 5 – 13–14, 6 – 12–13, 7 – 11–12, 8 – 10–11, 9 – 9–10.
To extrapolate the data of point observations of air temperature, various models are used that take into account mainly the characteristics of the relief, as well as atmospheric circulation, distribution of solar radiation, and other parameters [15, 16]. Such models are often based on data from meteorological stations, and they contain the general laws of temperature fluctuation when other parameters change, for example, a decrease in temperature with height. Meteorological stations on the territory of the Tunkinsky valley are located in plain open areas, analyzing their data, it is difficult to judge the climate of mountainous regions, as well as to study the microclimate. In addition, in the basin due to inversion processes, the general laws of temperature decrease with height are violated, which leads to erroneous calculations of such models. So, a comparison of air temperature indicators contained in the global climate database WorldClim,
with the results of our research [16]. The WorldClim dataset is freely available on the Internet and contains monthly regular network (raster) data on the minimum, maximum and average monthly air temperature, precipitation, altitude and other parameters. A comparison of the average monthly temperature in January and July revealed that the July temperature in the WorldClim model significantly (by 5–7 °C) differs from the data obtained by us, but on the whole correctly reflects the temperature change with height (decrease). The January temperature in the WorldClim model also decreases with height, which is not true, and differs from the data of field observations by 4–15 °C for the sides of the basin. This indicates that the model does not take into account winter temperature inversions.

The advantage of the remote method is the possibility of a local analysis of the spatial differentiation of air temperature, which is smoothed during landscape-interpretation mapping. However, remote sensing data contain inaccuracies, and also reflect only a certain time slice (time of survey), it is difficult to judge daily and seasonal changes in temperature, especially monthly average values.

The advantage of the landscape-interpretational mapping method is that the method allows you to map the average monthly and annual average air temperatures, which is difficult to do on the basis of remote sensing data that displays the temperature field at a particular point in time. The landscape approach when mapping meteorological elements allows you to take into account the influencing factors that have already been considered when compiling a landscape map, which greatly simplifies the mapping process. The use of a dense network of ground-based observations using thermographs is also improved the result of mapping.

Thus, a joint analysis of the data from a dense network of field observations, remote sensing data, and a landscape map made it possible to obtain spatial distribution patterns of the temperature regime for individual territories of the southwestern Baikal region. This made it possible to analyze the dynamics of the spatiotemporal distribution of the air temperature field with a relatively high degree of accuracy.

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