Cartographic Modeling of Soil Temperature Fields for Middle Siberia Transect Based on Conjoint Analysis of Automated Ground-based and Satellite Temperature Data[1]

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Abstract. A series of cartographic models was created basing on the conjoint analysis of quantitative indicators of the air and sols temperature regime, obtained by automated ground and satellite temperature sensors. It reflects the characteristics of temperature fields of typological units of soil-bioclimatic zonality for the Altai-Sayan region.

Key worlds: cartographic modeling; temperature fields; automated ground monitoring; satellite data.

1 Introduction

The relevance of development of the geographic information concept for mapping the soil cover, soil properties and regimes is presented in a large number of applications developed using geographic information systems and technologies. The temperature regime is one of the most significant environmental factors, which together with the hydrological regime characterizes the overall energy level of the formation and functioning of the soil cover. The temperature field of soils is a set of temperature values at points in the spatial region, which according to the results of studies obtained both in our country and abroad is considered as a leading factor in the structural and functional organization of soil cover. For thematic mapping, soil properties are used that closely correlate with the environmental characteristics and are due to the action of soil formation factors [1]. In the most complete form, the factors determining the properties of soils at a certain point in the studied space are reflected in the SCORPAN model, a soil spatially predicting function that assumes that the same combination of soil-forming factors-predictors correspond to soils of similar genesis, and the boundaries of soil structures are due to changes in soil differentiation factors. The most informative predictors are selected using the pedotransfer method approaches, which allow calculating pedotransfer functions – communication equations that describe the functional relationships of basic soil properties and characteristics of soil geographic space [2]. The main difference of this methodology is that, based on the totality of the selected quantitative soil-ecological indicators, we can proceed to its taxonomic characterization. This approach allows for the aggregate of homogeneous soil-forming predictor factors to spatially separate the areas of soils and draw contour boundaries between them. Cartographic models of temperature fields obtained as a result of a joint analysis of ground-based and satellite data are sufficiently informative with respect to the energy of soil-forming processes and can be used to assess the thermal conditions of soils in poorly explored and inaccessible territories of the Altai-Sayan region.

2 Study area and data

Testing of the methodological provisions for identifying the boundaries of temperature fields was carried out on the example of typological units of the soil cover of the Altai-Sayan region, including a variety of steppes of the Chulym-Yenisei and Minusinsk troughs, the Chuy, Kurai, Turan-Uyuk, Central Tuva, Ubsu-Nur basins and tundra-steppe complexes Ukok Plateau. The key areas were selected taking into account the principles of landscape zoning, which allows one to recognize, classify, and map landscape differentiating factors, landscape components, the regional landscape structure as a whole, and its dynamic features. The method is based on a coupled analysis of regional structures objectively reflected in satellite images and recorded on landscape-typological maps. Landsat 8/9 satellite images were used as information sources. Thematic soil and climate maps were used as auxiliary maps for decoding satellite images. The intermountain basins of Khakassia and Tuva are located in the eastern sector of the Altai-Sayan mountain region in the following sequence from north to south - Severo-Minusinskaya, South Minusinskaya, Turano-Uyuk, Central Tuva and Ubsu-Nurskaya. The elevations of the bottoms of the basins increase southward from 300 to 500 m above sea level **i**n the basins of Khakassia and from 700 to 900 m above sea level in the basins of Tuva. In the same direction, climate continentality increases – from the mildest climatic conditions in the North Minusinsk to the most severe type of thermal regime in the Ubsu-Nur basin. Distribution features and conditions for the formation of thermal conditions in the steppes of the left bank of the Yenisei-Minusinsk depression (Khakassia) are associated with their location between the mountain structures of the Kuznetsk Ala-Tau, East and West Sayan.

On the territory of Tuva, the Turano-Uyuk, Central Tuva and Ubsu-Nur steppe basins are clearly distinguished by climate-forming factors and thermal conditions of soil formation. Within the boundaries of the Ukok highlands, tundra-steppe complexes with a contrasting combination of mountain-steppe and mountain-tundra soils and quantitative indicators of the soil climate stand out. The contrast of the climatic regimes of air and soils in the basins of Khakassia is formed depending on the severity of the direction of moisture transfer, which in the eastern sector of the Altai-Sayan mountain region has a western, alternating with a northwestern orientation (Table 1).

Climatic conditions, as a set of environmental factors, have a direct impact on the formation of the diversity of the soil cover in the hollow steppes of Khakassia. In the regions of the Uzhuro-Kopiev and Shirin steppes, in which the average annual air temperature is 1,3 °C, the frost-free period is 168 days and $\Sigma t^\circ > 10^\circ C = 1573^\circ$ southern and ordinary chernozems prevail, occupying from 14 to 34% of the area.

In the Uybat steppe, located in close proximity to the eastern foothills of the Kuznetsk Ala-Tau, the average annual air temperature is -1,1 °C, the frost-free period is 170 days and $\Sigma t^\circ > 10^\circ C = 1630^\circ$. Therefore, the most xerophilous core of the steppe vegetation is located here and low-fertile solonetzic soils are formed. In the Tuva basins clearly differing in physical and geographical environmental conditions, annual and daily climate cycles, temperature fields are distinguished, which can be considered as indicators of differences in the complex of climatic conditions and the structural organization and functioning of the soil cover (Table 2).

Table 1. Air and soil temperature regime indicators by of the soil profile depths (cm) for Khakassia steppe basins.

Temperature indicators, T°C	Air temperature T°C	Soil temperature by the depths of the soil profile (cm), T°C				
		on the soil surface	10	20	30	50
Uzuro-Kopievskaya meadow steppe, Kopievo (N54°56'19,6"; E89°52'47,1")						
>10°	1461,5/89*	1674,5/100	1427,2/90	1400,7/90	1205,3/77	1202,9/83
>5°	1755,3/131	1917,3/133	1742,8/133	1711,8/132	1571,8/123	1508,5/126
>0°	1845,6/168	2026,7/176	1827,2/173	1819,3/183	1706,3/179	1631,8/177
<0°	-1420,9/165	-1118,5/157	-1035,3/160	-879/150	-817,9/154	-642,8/156
average annual temperature	1,3	2,7	2,4	2,8	2,7	3,0
Shirinsky lake-basin steppe, lake Tus (N54°45'17,2"; E89°57'17,9")						
>10°	1558,8/90	1875,1/105	1707,9/100	1428,1/90	1359,9/87	1075,6/76
>5°	1859,6/130	2161/144	2020,7/141	1760,9/136	1721/135	1422,8/124
>0°	1974,5/169	2244,2/181	2127,2/185	1846/172	1842,5/183	1554,3/177
<0°	-1544/164	-1168,2/152	-980/148	-973,7/161	-720,8/150	-639/156
average annual temperature	1,3	3,2	3,4	2,6	3,4	2,7
Uybat plain-hilly solonetzic steppe, lake Ulug-Khol (N53°47'30,1"; E90°38'39,8")						
>10°	1630,8/95	1785,7/105	1457,8/94	1363,7/90	1168,5/80	1091/79
>5°	1927,1/135	2059,4/142	1732,8/130	1674,9/132	1523/127	1407,8/121
>0°	2010,1/170	2118,6/164	1829,3/170	1767,4/169	1634,9/166	1553,8/174
<0°	-1638,4/163	-1796,6/169	-1546/163	-1367,8/164	-1245,5/167	-1022,5/159
average annual temperature	1,1	1,0	0,9	1,2	1,2	1,6

* the denominator is the number of days

Table 2. Air and soil temperature regime indicators by the soil profile depths (cm) for Tuva steppe basins.

Temperature indicators, T°C	Air, temperature T°C	Soil temperature by the depths of the soil profile (cm), T°C				
		on the soil surface	10	20	30	50
Turan-Uyuk basin, Turan (N52°08'18,8"; E93°49'25")						
>10°	1572,8/95*	1754,1/96	1470,3/88	1284,9/82	908,9/70	1572,8/95*
>5°	1768,5/121	1951,4/124	1726/124	1536,5/116	1210,3/112	1768,5/121

>0°	1874/160	2026,5/152	1822,8/161	1660/163	1312,7/156	1874/160
<0°	-2626,3/169	-2112,3/177	-843,8/168	-693,5/166	-270,3/171	-626,3/169
average annual temperature	-2,3	-0,3	-0,1	-0,1	0,1	-2,3
Ulug-Khem Basin, Kyzyl (N51°44'36,5"; E94°19'34,4")						
>10°	2043,3/107	2327,3/120	1995,1/112	2151,3/121	1730,1/107	2043,3/107
>5°	2349,9/149	2603,5/156	2268,9/148	2458,9/163	2083,8/156	2349,9/149
>0°	2440,7/180	2672,4/183	2350,5/179	2515,4/192	2157/183	2440,7/180
<0°	-2319,2/149	-1882,5/146	-752,3/150	-388,8/137	-1234/126	-319,2/149
average annual temperature	0,4	2,4	1,8	3,4	2,8	0,4
Khemchik depression, Ak-Dovurak (N51°13'0,2"; E90°31'38")						
>10°	2034,2/110	2484,9/125	2238,1/121	2155,7/118	2117,8/117	2034,2/110
>5°	2320,7/148	278,4/154	2450,5/149	2399,7/150	2376,7/151	2320,7/148
>0°	2383,6/174	2767/177	2511,3/175	2459,7/173	2440,3/170	2383,6/174
<0°	-2586,9/155	-2199,8/152	-159,5/154	1994,9/156	-1844/159	-586,9/155
average annual temperature	-0,6	1,7	1,1	0,6	1,8	-0,6
Ubsu-Nur Basin, lake Tere-Khol (N50°15'23,4"; E95°0,2'32,3")						
>10°	2207/125	2575/132	2400/133	2320/131	2226/128	2207/125
>5°	2407/151	2755/155	2522/150	2480/154	2448/158	2407/151
>0°	2461/169	2830/182	2603/179	2542/179	2496/179	2461/169
<0°	-3114/172	-2035/159	-2024/162	-1884/162	-1613/162	-3114/172
average annual temperature	-1,9	2,3	1,7	1,9	2,6	-1,9

* the denominator is the number of days

The Turano-Uyuk Basin, located at an altitude of 700-900 m above sea level according to the main indicators of the climatic regime – the average annual air temperature (-2.3°), the duration of the frost-free period (160 days) and $\Sigma t^\circ > 10^\circ C = 1573^\circ$, it approaches the conditions of the arid steppe zone. Thermal conditions of the Ulug-Khem and Khemchik hollows, the bottoms of which are 600-800 m above sea level, characterized by a higher average annual air temperature (-0.4°), a longer frost-free period (180 days) and $\Sigma t^\circ > 10^\circ C = 2043^\circ$. The Ubsu-Nur basin is distinguished by a low atmospheric humidification and high heat resources of summer: average annual air temperature (-1.9°), frost-free period – 169 days and $\Sigma t^\circ > 10^\circ C = 2034^\circ$, which create a regime semi-desert zone with chestnut soils and psammozems.

3 Ground-based automated monitoring of air and soils

Ground-based automated monitoring of air and soil was organized using a specialized temperature recorder DS-1921G “Thermochron” taking into account indicators reflecting the genetic unity of the climate types of the Altai-Sayan region. To fix the air temperature, an autonomous recorder was installed at a height of 2 m from the soil surface under conditions excluding direct radiation exposure. The dynamics of temperature changes on the soil surface and horizons of the soil profile was recorded during the year with an interval of 4 hours. As a result of the observations, a large amount of evidence was obtained, which was used as the basis for calculating the thermal resources of temperature fields and identifying their time trends [3].

4 Software and algorithms for MODIS data retrospective analysis, statistical processing and visualization

Thematic processing of satellite images was carried out using the original nonparametric methods and technologies for satellite images segmentation proposed by the authors, which allow taking into account both spectral and spatial features, as well as ground-based observations [4-7].

For retrospective analysis, statistical processing and visualization of MODIS data were used the original software and algorithmic tools created at ICT SB RAS, based on a new technology for access to the satellite data archive implemented using the PostgreSQL DBMS with an additional module [4, 5]. This module is designed for direct access to the file data archive without the need for preliminary copying and converting the data format for the DBMS. It implements transparent mapping of the satellite image file archive into virtual database tables. The module allows you to execute arbitrary SQL queries to the file archive data, while the query planner optimizes their execution based on available metadata, and the algorithms used to perform the calculations provide for work with information volumes exceeding the DBMS server RAM capacity. The developed system for extracting data from the satellite imagery archive can be compared with such systems as NASA Giovanni, Google Earth Engine and the European project TELEIOS. All are aimed at providing access to large volumes of satellite imagery. The created technology surpasses the described systems in various aspects. There are no restrictions on the type of data queries, since arbitrary SQL queries are supported. This system is designed to work with arbitrary spatial data without the need for their preliminary transformation and preparation.

5 Cartographic modeling of the soil temperature fields heterogeneity

An interpretation of typological units of structural and functional organization for soil cover of steppe basins is presented on the basis of a statistical analysis of the combination of boundaries and the information content of the soil cover contours and the temperature field contours obtained from the analysis of satellite data of day and night temperatures and the temperature difference of subtraction of two compiled series calculated for 16 year period (2001-2016).

The possibility of cartographic modeling of the structural organization and functioning of the soil cover was revealed using steppe basins of the Middle Siberian transect and tundra-steppe complexes of the high mountains of the Altai-Sayan region as an example. The interpretation of typological units of the structural and functional organization of the soil cover of the steppe basins of Khakassia is presented on the basis of a statistical analysis of the combination of boundaries and the information content of the soil cover contours and temperature fields obtained by analyzing satellite data of daytime, nighttime temperatures and temperature differences obtained by subtracting two compiled series (Figure 1).

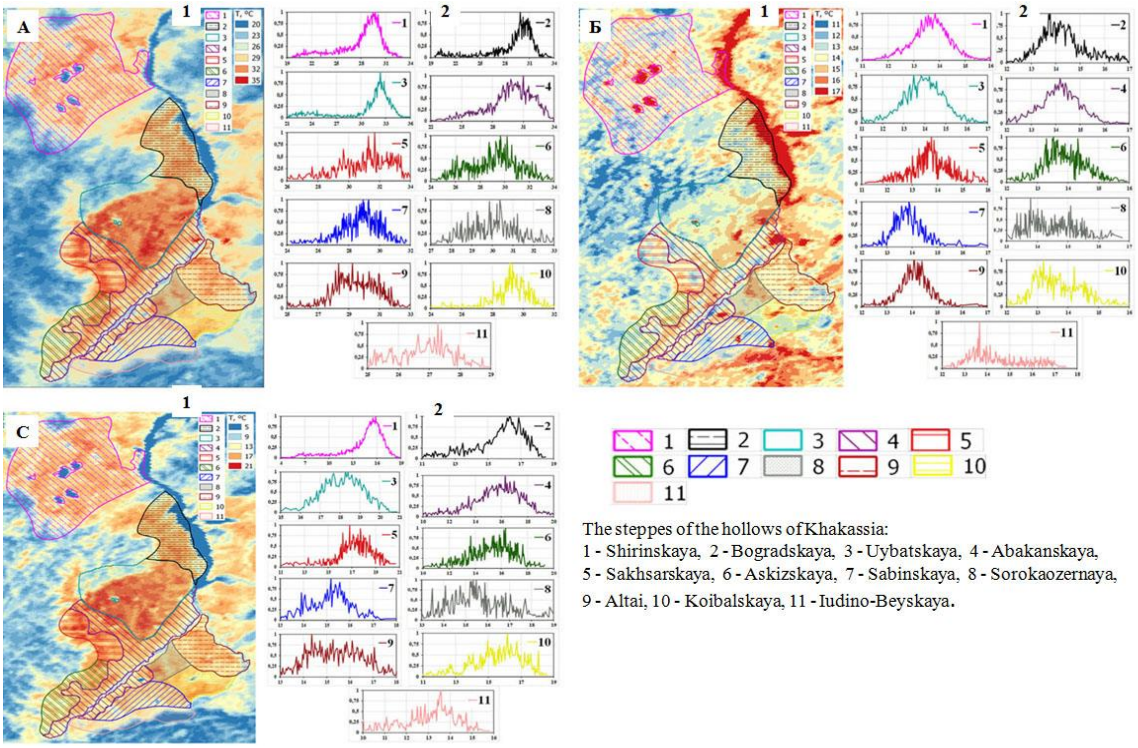

Figure 1. Cartographic models of the temperature fields of the steppes of Khakassia. A – daytime, B – nighttime and C – temperature differences obtained by subtracting two compiled series. 1- temperature fields; 2 – statistical analysis of combining the boundaries of soil contours and temperature fields.

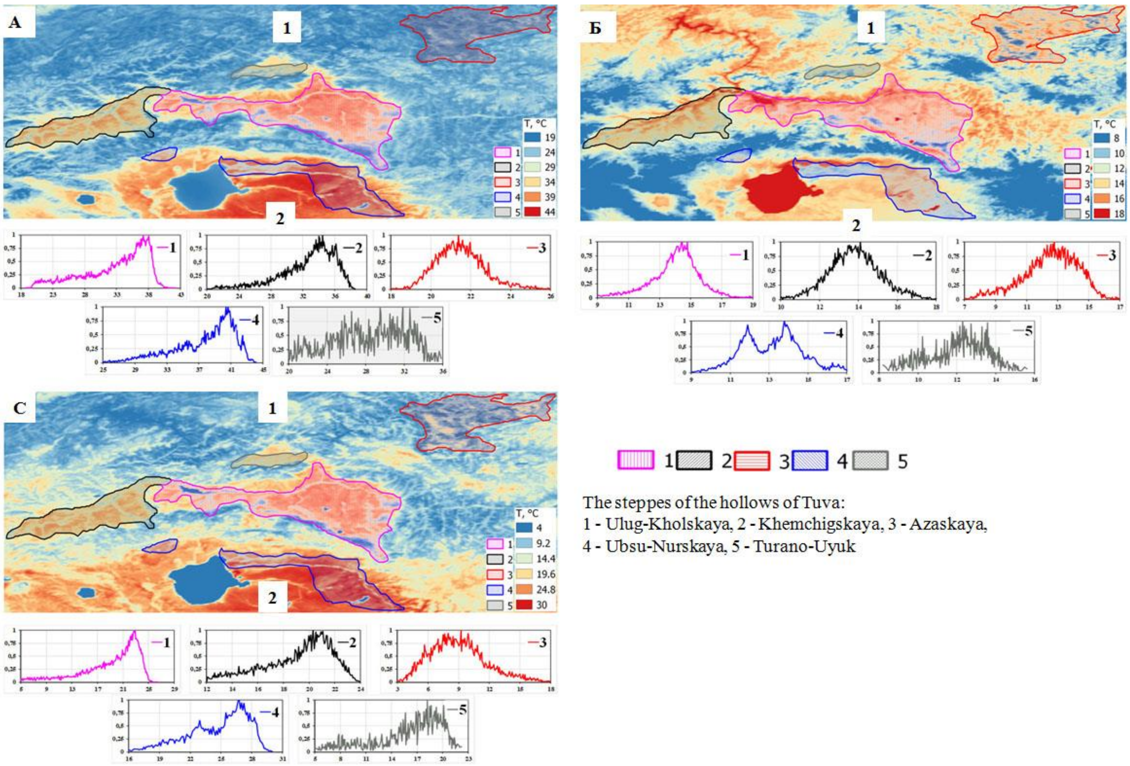

Figure 2. Cartographic models of the temperature fields of the steppes of Tuva. A – daytime; B – nighttime and C – temperature differences obtained by subtracting two compiled series. 1 – temperature fields; 2 – statistical analysis of combining the boundaries of soil contours and temperature fields.

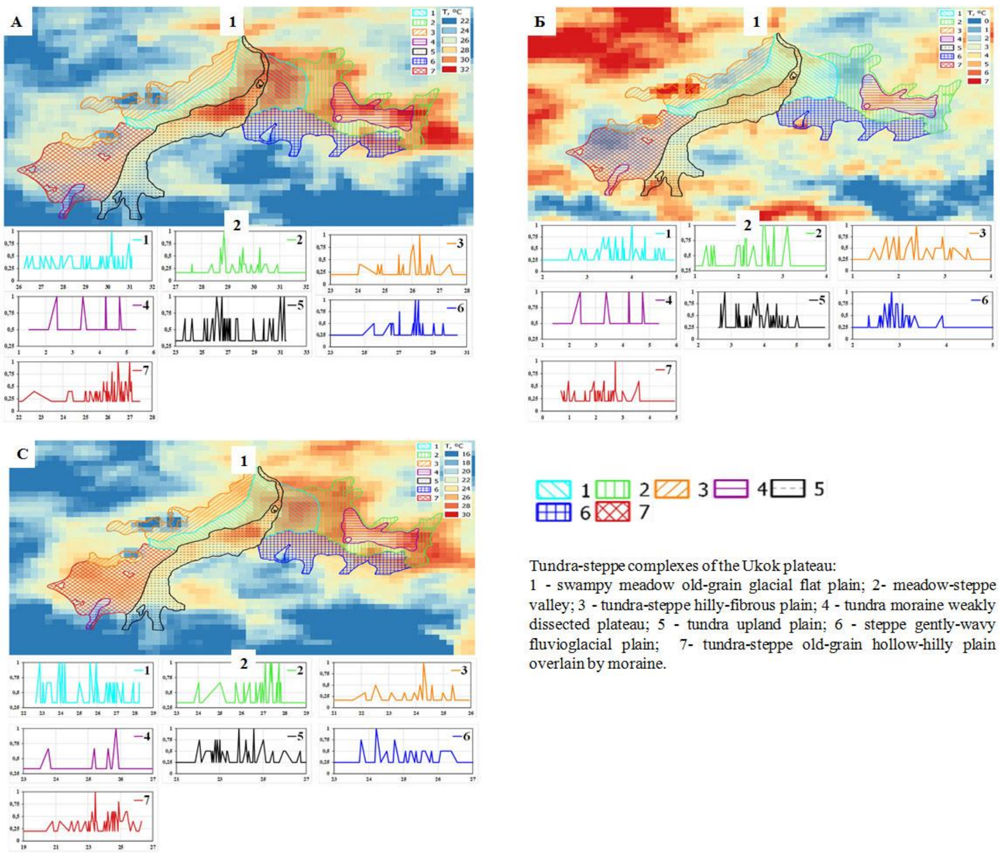

Figure 3. Cartographic models of the temperature fields of the tundra-steppe complexes of Ukok plateau. A – daytime; B – nighttime and C – temperature differences obtained by subtracting two compiled series. 1 – temperature fields; 2 – statistical analysis of combining the boundaries of soil contours and temperature fields.

The obtained cartographic models give a clear idea of the boundaries of the temperature field contours of typological units of the soil cover of Khakassia, the functioning of which is carried out in a wide range of temperatures. They make it possible to get an idea of the thermal conditions of both large units of soil cover, such as the Shirinskaya or Uybatskaya hollows, and occupying small areas – Koibalskaya or Sorokaozernaya, but having independent environmental significance. Noteworthy are the significant difference in the allocation of areas of soil contours and their temperature fields in the basins of dry (deserted) steppes, obtained on the basis of the analysis of satellite data, both day and night temperatures. The spatial distribution of temperature fields, taking into account current trends in thermal resources, can be used to adjust the contour boundaries of the structural units of the soil cover.

The spatial distribution of temperature fields in the steppe basins of Tuva has a southwestern direction and is due to the peculiarities of the macro relief. In the basins of Tuva, characterized by a high degree of diversity of characteristics of the soil geographical space and aridization of the climate, the obtained cartographic models of temperature fields can be used to identify spatial and temporal gradients of thermal resources at the scale of large and local soil cover units (Figure 2).

Cartographic models of temperature fields are also informative for identifying the conditions of heat supply for the formation and functioning of the tundra-steppe complexes of the Ukok highlands, for the soil cover of which combinations of mountain-steppe and mountain-tundra soils are typical (Figure 3).

Temperature field models can be used to obtain additional information about natural complexes, the formation and functioning of which is carried out under conditions of ultra-high or ultra-low temperatures**.**

In general, cartographic models of temperature fields obtained as a result of a joint analysis of terrestrial and satellite data are sufficiently informative with respect to the energy of soil-forming processes and can be used to assess the thermal conditions of soils in insufficiently studied and inaccessible territories of the Altai-Sayan region.

The novelty of the approach lies in the fact that cartographic models of soil temperature fields, created on the basis of quantitative indicators of the temperature regime, have sufficient information content to establish relationships with other characteristics of environmental objects and to solve the problem of distinguishing the boundaries of temperature fields of typological units of soil cover.

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