Application of an Unmanned Aerial Vehicle for Large-Scale Mapping of Thermokarst Landforms

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Abstract. thermokarst refers to cryogenic processes, as a result of which characteristic relief forms are formed, as a result of melting of icy frozen soils or an ice complex. The study of the dynamics and distribution of modern thermokarst forms is important from the point of view of using them as one of the main indicators of the degradation of permafrost soils. In recent years, unmanned aerial vehicles, which can create orthorectified images and digital terrain models (DTM) with very high spatial resolution, have been actively used to study thermokarst. This article provides an example of the use of UAVs in the study of the development of thermokarst in s. Uncure. Based on landscape-geomorphological studies and decoding of the created orthophotomap, the areas of thermokarst development were identified. The total land area covered by thermokarst is 0.66 km², which is 19.5% of the territory of the settlement. According to the classification of P.A. Solovyov, two types of thermokarst relief were distinguished here: bylary and alas. The largest area is covered by bylars, which are the initial stage of the formation of Alas. They are formed as a result of melting of the upper part of vein ice and form a polygonal-lowland microrelief. More than 6,000 elementary polygons with a total area of 0.4 km² were discovered here. The landfill area varies from 6 m² to 22 m², and the average area is 57 m². They are formed by local areas throughout the area of the village.

1. Introduction

Ice-rich sediments comprise a significant portion of permafrost in East Siberia, mostly in its Arctic and Subarctic regions [1]. In the Republic of Sakha (Yakutia), they underlie 31% of the total land area [2]. Ice-rich permafrost is particularly susceptible to thawing induced by climatic warming. Recent investigations in Central Yakutia indicate rapid thermokarst development, with surface subsidence occurring at rates up to 10-15 cm/year [4, 4]. Thermokarst is the process by which characteristic landforms result from the thawing of ice-rich permafrost or ice complex [5]. Understanding the distribution and dynamics of newly formed thermokarst landforms is important because they serve as a useful indicator of permafrost degradation. Their development is associated with landscape modifications resulting from climatic change [3, 6]. Thermokarst is presently more rapid in open natural and anthropogenic landscapes [7, 8] with a thin transient layer (0.2 m), i.e. an ice-rich zone at the active layer–permafrost interface [9], compared to the areas covered by boreal forest where the transient layer is 0.7 to 1.0 m thick [8]. The transient layer has a very high content of ice (up to 60–70%) which forms massive-agglomerate and reticulate...
cryostructures. Silty soil textures predominate in this layer [1]. Climatic warming causes destruction of the transient layer which protects the underlying permafrost from thaw [10]. This leads to rapid thermokarst processes [11].

It is estimated that 33.6% of infrastructure in Yakutia will be affected by permafrost degradation and thermokarst by the mid-21st century, with high associated costs for the region [12]. Many communities located in the areas underlain by ice-rich permafrost and ice complex will be particularly at risk. Investigations of thermokarst activity in such communities are therefore important, because they will help develop measures for early prevention and prediction of thaw-related hazards.

Remote sensing that combines the use of satellite and aerial imagery with detailed field observations is an effective method to study thermokarst [13]. However, this approach has limitations because smaller topographic features are not fully detected due to the low resolution of images, making it difficult to reliably assess the degree of thermokarst development. In recent years, unmanned aerial vehicles (UAV) have been increasingly utilized in studies of thermokarst and other permafrost features [4, 14, 15]. UAV surveys can provide orthorectified images and digital elevation models (DEMs) with very high spatial resolution (< 1.0 m/pixel).

The objective of this study was to evaluate the development of thermokarst in the Yunkur Village area. To this end, the study included field observations, UAV aerial survey and data analysis using specialized software. The work is an initial phase in the development of monitoring observations of thermokarst dynamics. Such observations are essential to obtain information critical for predictive assessments of ice-rich permafrost degradation.

2. Study

Yunkur Village is located in the left Lena River valley 6 km northwest of the city of Olekminsk, southwestern Yakutia (Fig. 1). Geomorphologically, the study area lies on a 60 to 65 m high alluvial terrace in the transition zone between the Lena-Aldan flat plateau and the Pre-Vilyui flat trap plateau. Its hypsometry correlates with the Magan terrace of the middle Lena River [16]. The terrace is separated from younger terraces by a steep scarp with Cambrian limestone and dolomite exposed at the foot. The terrace material consists of silts which contain ice wedges up to 10 m thick. The surface is characterized by the presence of shallow depressions with no distinct margins, as well as the widespread occurrence of mid-Holocene alas basins, up to 15 m in depth. The climate of the area is strongly continental. The mean annual air temperature at a nearby meteorological station (Olekminsk) is -6.7°C. Monthly means are -32.2°C for January and +18.0°C for July. Mean annual precipitation in the region is 315 mm.

Knowledge of permafrost conditions in the area is limited and is mostly contained in internal research reports of the Melnikov Permafrost Institute and geotechnical exploration records. First data on the permafrost were obtained by Alexander von Middendorf in 1846 when he measured ground temperatures in a pit near Olekminsk. Systematic geocryological investigations were begun in 1950 by the Yakutsk Permafrost Station, which provided information on permafrost thickness along the Lena River valley between the towns of Nokhtuisk and Sagynyakhtakh. Later, studies were conducted in the Ust-Biryuk rock salt field, 60 km west of Olekminsk. As a result, series of maps and cross-sections were obtained showing mean annual ground temperatures and active-layer depths. In the 1990s, studies were carried out to characterize the engineering properties of permafrost materials below the runway at Olekminsk Airport. These studies provided additional information on permafrost conditions near Olekminsk and confirmed the widespread occurrence of wedge ice in the area.

According to the Permafrost-Landscape Map of Yakutia [2], the study area is situated within the Nuya-Olekma Province with discontinuous permafrost 100 to 150 m in thickness [17]. Permafrost temperatures at the depth of zero annual amplitude range between -0.2°C and -1.0°C, and active-layer thicknesses vary from 1.6 m in wet boreal forests to 3.0 m at open sites [2].
3. Methods
Field investigations were conducted in early September 2019 to examine the landscape and geomorphological conditions and to obtain an orthomosaic of the study area. Aerial images were taken with a DJI Mavic 2 Pro quadcopter which houses a 20-megapixel camera and records coordinates. Flights were made in autonomous mode using the specialized software. The flight altitude was 200 m above ground level, allowing 70% overlap to be achieved. In all, 1341 images were acquired. Ground control points (GCPs) were established to georeference the imagery and their coordinates were measured using a survey-grade GNSS-receiver (Trimble 5700) in static mode. A total of 10 GCPs were setup with a <3 cm accuracy level. The aerial images were processed using Agisoft PhotoScan with the GCPs as markers. An orthomosaic and digital elevation model with spatial resolution of 1.5 cm/pixel were derived covering an area of 3.4 km². The orthomosaic was further processed in ArcMap 10.1 software. Interpretation was performed in manual mode, while statistical parameters were computed automatically using the software modules.

4. Results and discussion
Based on the field terrain observations and interpretation of the derived orthomosaic, a schematic map of thermokarst development at Yunkur was compiled at a scale of 1:8,000 (Fig. 2).
The total area affected by thermokarst was estimated to be 0.66 km², comprising 19.5% of the village area. Two thermokarst landforms were identified – alases and bylars, following the classification by Soloviev [16]. Bylars form during the initial stage of thermokarst when the deepening active layer reaches the top of ice wedges resulting in a polygonal network of troughs surrounding high-centered polygons. Over 6000 elementary polygons were identified totaling 0.4 km² in area (Fig. 3). Individual polygons vary in area from 6 to 223 m², with an average of 57 m².

Figure 3. Destructive effects of bylars on infrastructure, Yunkyur Village: a – Thaw-induced ground subsidence beneath the floor damaged the house, b – Thermokarst troughs and pits made the vegetable garden unusable.

Analysis of the derived map (see Fig. 2) indicated a clustered distribution of thermokarst-induced polygons across the entire village area. However, they are more abundant in the north-western part of the village where they occur between the lakes and along the lake edges. The size range of the polygons is close to that of similar features observed by Saito et al. on abandoned arable land in Churapcha, Central Yakutia [4]. The results of that study suggest that the polygon size is controlled by ice-wedge morphology and ground-ice content. In particular, the observed range of polygon sizes (6 to 223 m²) is associated with the degradation of secondary ice wedges with the maximum transverse dimension of 8 m.

The development of polygonal landforms adversely affects land use in Yunkur. Some residents have had to relocate their houses because of thaw subsidence resulting in deep troughs around the polygons. The depth of troughs ranges in the study area from a few centimeters to 1.87 m (Fig. 4). As reported in the literature [4], subsidence rates over thermokarst troughs can be as high as 12 cm/year. Conversations with local residents indicate that ground subsidence in Yunkur has been occurring since the early 1990s. This is consistent with data from the Olekminsk weather station which show a 1.2°C rise in mean annual air temperature since the 1990s [18] and a linear trend of 0.4°C in soil temperature at 3.2 m depth [19]. These warmer temperatures have resulted in increased active-layer depths and thermokarst activity.

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.
Bylar site in the northwestern part of Yunkur (a, b) and its transverse profile (c).

Older thermokarst basins, or alases, are also present in the study area, along with recent thaw-related features. Their total area is 0.26 km². The largest alas is located in the northeastern part of Yunkur. It has a round shape with a diameter of 380 m and a depth of 10 m. Its low-lying part is covered by a lake with a surface area of 0.05 km². The alases are of Holocene age, as inferred from their morphological characteristics. Some theories suggest that alas basins in East Siberia began forming during the Pleistocene-Holocene transition [13, 20], reaching peak activity during the Holocene Optimum with its climate comparable to the current climatic change [12]. The warmer conditions caused rapid thermokarst development at that time. One study [21] suggests that thermokarst basins might have grown to a size of 120-600 m diameter and 7.5-15.0 m depth within only ~150 years.

Conclusions
From the results of this study it can be concluded that unmanned aerial vehicles provide a useful tool for landscape investigations. This advanced, high-tech method can be effectively utilized in permafrost research, as demonstrated by the application of UAV to map thermokarst-affected areas in the village of Yunkur. The high resolution of the orthomosaic made it possible to identify polygonal features which result from the thawing of the uppermost part of the ice complex and indicate the initiation of permafrost degradation. Thaw subsidence of the land surface is already a serious concern to the residents of Yunkur. Further monitoring observations over several years will be needed to more reliably evaluate thermokarst dynamics and predict its future trends.

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6. Reference
[1] Konishchev V N 2011 The reaction of permafrost to climate warming Earth’s Cryosphere vol XV 4 pp 15-18
[2] Fedorov A N, Vasilyev N F, Torgovkin Ya I, Shestakova A A, Varlamov S P, Zheleznyak M N, Shepelev V V, Konstantinov P Y, Kalinicheva S S, Basharin N I, Makarov V S, Ugarov I S, Efremov P V, Argunov R N, Egorova L S, Samsonova V V, Shepelev A G, Vasiliev A I, Ivanova R N, Galanin A A, Lytkin V M, Kuzmin G P and Kunitsky V V 2018 Permafrost-landscape map of the Republic of Sakha (Yakutia) on a Scale 1:1500000 Geosciences vol 8 12 pp 465
[3] Fedorov A N, Gavriliev P P, Konstantinov P Y, Hiyama T, Iijima Y and Iwahana G 2014 Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia Ecohydrology vol 7 2 pp 188-196
[4] Saito H, Iijima Y, Basharin N I, Fedorov A N and Kunitsky V V 2018 Thermokarst development detected from high-definition topographic data in Central Yakutia Remote Sensing vol 10 10 pp 1579
[5] Kachurin S P 1961 Thermokarst in the USSR (Moscow Publishing House of the USSR Academy of Sciences)
[6] Fedorov A N and Konstantinov P Y 2008 Recent changes in ground temperature and the effect on permafrost landscapes in Central Yakutia Proceedings of the Ninth International Conference on Permafrost (Fairbanks: AK) pp 433-438.
[7] Fedorov A N, Iwahana G, Konstantinov P Y, Machimura T, Argunov R N, Efremov P V, Lopez L M C and Takakai F 2017 Variability of permafrost and landscape conditions following clear cutting of larch forest in Central Yakutia Permafrost and Periglacial Processes vol 28 1 pp 331-338
[8] Fedorov A N, Konstantinov P Y, Vasilyev N F and Shestakova A A 2019 The influence of boreal forest dynamics on the current state of permafrost in Central Yakutia Polar Science vol 22 p 100483
[9] Efimov A I and Grave N A 1940 Buried ice in the Abalakh lake area Socialisticheskoe Stroitistvo 10-11 pp 67-78
[10] Shur Y, Hinkel K M and Nelson F E 2005 The transient layer: implications for geocryology and climate-change science Permafrost and Periglacial Processes vol 16 1 pp 5-17
[11] Grosse G, Romanovsky V, Jorgenson T, Anthony K W, Brown J and Overduin P P 2011 Vulnerability and feedbacks of permafrost to climate change. Eos, Trans. actions American Geophysical Union vol 92 9 pp 73-74
[12] Streletskiy D A, Suter L J, Shiklomanov N I, Porfiriev B N and Eliseev D O 2019 Assessment of climate change impacts on buildings, structures and infrastructure in the Russian regions on permafrost Environmental Research Letters vol 14 2 pp 25003
[13] Grosse G, Schirrmeister L, Siegert C, Kunitsky V V, Slagoda E A, Andreev A A and Dereviagyn A Y 2007 Geological and geomorphological evolution of a sedimentary periglacial landscape in Northeast Siberia during the Late Quaternary Geomorphology vol 86 1-2 pp 25-51
[14] Khairullin R R, Khomutov A V, Dvonnikov Yu A, Babkin E M, Babkina E A and Soshchenko D D 2019 Analysis of peatland changes in the northeastern part of the Pur-Taz interfluve based on remote sensing and ground monitoring data Current Problems in Remote Sensing of the Earth from Space vol 16 4 pp 54-62
[15] Kartozia A 2019 Assessment of the ice wedge polygon current state by means of UAV Imagery analysis (Samoylov Island, the Lena delta) *Remote Sensing* vol 11 13 pp 1627

[16] Soloviev P A 1959 Permafrost of northern part of the Lena-Amga interfluve (Moscow: Publishing house of the USSR Academy of Sciences)

[17] Geocryological Map of the USSR Scale 1: 2500000 1991 (Vinnitsa: Vinnitsa Cartographic Factory)

[18] Skachkov Yu B 2016 Mean annual air temperature variation in the Republic of Sakha (Yakutia) during the last 50 years (Yakutsk: Energy balance and climate over the boreal and arctic regions with special emphasis on Eastern Eurasia, Proceedings of the IXth International Symposium) pp 208-211

[19] Streletskiy D A, Sherstiukov A B, Frauenfeld O W and Nelson F E 2015 Changes in the 1963–2013 shallow ground thermal regime in Russian permafrost regions *Environmental Research Letters* vol 10 12 pp 125005

[20] Katamura F, Fukuda M, Bosikov N P and Desyatkin R V 2009 Charcoal records from thermokarst deposits in central Yakutia, eastern Siberia: implications for forest fire history and thermokarst development *Quaternary Research* vol 71 1 pp 36-40

[21] Ulrich M, Wetterich S, Rudaya N, Frolova L, Schmidt J, Siegert C, Fedorov A N and Zielhofer C 2017 Rapid thermokarst evolution during the mid-Holocene in Central Yakutia, Russia *The Holocene* vol 27 12 pp 1899-1913

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