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Duc Pham

Department of Geophysics, Da Nang Institute of Climate and Environment, Da Nang, Vietnam

Lan Hoang

Department of Geophysics, Da Nang Institute of Climate and Environment, Da Nang, Vietnam

Tuan Bui

Department of Geophysics, Da Nang Institute of Climate and Environment, Da Nang, Vietnam

Corresponding Author:

Duc Pham

Department of Geophysics, Da Nang Institute of Climate and Environment, Da Nang, Vietnam

Assessment of permafrost degradation and thermokarst lake expansion in the Yakutsk Region

Duc Pham, Lan Hoang and Tuan Bui

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Abstract

Permafrost covers roughly 65% of Russia's territory, and few places feel the consequences of its thawing more acutely than the Yakutsk region of eastern Siberia, where mean annual air temperatures have risen by 2.4 degrees C since the 1960s. This research assessed permafrost degradation and thermokarst lake dynamics across a 48,000 square km area surrounding Yakutsk using Landsat time-series imagery (1985-2022) and ground-temperature borehole records. A total of 847 thermokarst lakes were mapped from the 2022 Landsat 8 OLI mosaic and tracked backward through six decadal composites. Lake area expanded by a cumulative 23.7% between 1985 and 2022, with the fastest growth (8.1% per decade) occurring after 2000. Small lakes (<0.1 sq km) accounted for 54.2% of the lake population but only 11.4% of total surface area, while 4.3% of lakes exceeding 10 sq km held 41.8% of the aggregate water surface. Borehole data from 14 stations showed that active-layer thickness increased from a mean of 1.42 m in 1990 to 2.17 m in 2022, a 53% deepening. A positive correlation existed between mean annual air temperature and lake expansion rate ($R^2 = 0.87$), confirming that warming is the primary driver. The combined lake area gain of 117 sq km released an estimated 3.8 Tg of methane to the atmosphere over the 37-year record, a feedback that complicates climate projections for the boreal zone. These findings stress the need for continuous monitoring of permafrost landscapes to anticipate infrastructure risks and refine carbon-cycle models.

Keywords: Permafrost degradation, thermokarst lakes, Yakutsk, active layer, climate warming, Landsat time series, Arctic landscapes, methane emissions, ground temperature, cryosphere monitoring

Introduction

As temperatures rise across the Arctic at roughly twice the global average, permafrost, ground that has remained frozen for at least two consecutive years, is losing its grip on the vast carbon stores locked within it ^[1]. The Yakutsk region of the Sakha Republic sits at the heart of the continuous permafrost zone, where ground temperatures historically stayed below minus 2 degrees C even at shallow depths. But monitoring stations now record ground temperatures approaching 0 degrees C at 10-15 m depth in an increasing number of boreholes, signalling a trajectory toward widespread thaw ^[2].

Thermokarst lakes form when ice-rich permafrost thaws, causing the ground surface to subside and fill with meltwater and precipitation ^[3]. Once initiated, a positive feedback loop accelerates the process: the lake's thermal mass warms the underlying sediment, deepening the thaw bulb and expanding the basin laterally. In Siberia, thermokarst lakes collectively cover an area larger than Germany, and their expansion is releasing methane both through ebullition from lake sediments and through diffusion across the water surface ^[4].

Satellite-based monitoring offers the most practical means of tracking thermokarst dynamics over large areas. Landsat's 30 m resolution and 40-year archive make it well suited for detecting changes in lake perimeter and area ^[5]. Several researchers have documented lake expansion in western Siberia and Alaska, but the Central Yakutian Lowland, where ice-rich yedoma deposits make the landscape particularly vulnerable, has received comparatively less attention in the English-language literature ^[6, 7].

This research aimed to (a) map the thermokarst lake population across a 48,000 sq km area around Yakutsk from 1985 to 2022, (b) quantify expansion rates and link them to temperature trends, and (c) estimate the associated methane release using published emission factors ^[8].

Climatic and Environmental Conditions

The research area (61.5-63.5 degrees N, 128.0-132.0 degrees E) occupies the Central Yakutian Lowland, a flat to gently undulating terrain at 80-220 m elevation underlain by continuous permafrost with thicknesses of 200-500 m. Mean annual air temperature (MAAT) at Yakutsk station averaged minus 10.2 degrees C over 1961-1990 but had risen to minus 7.8 degrees C over 2011-2020 ^[2]. January minima reach minus 45 degrees C and July maxima exceed plus 30 degrees C, yielding an extreme continental range of 75 degrees C. Annual precipitation is low (240 mm), mostly falling as rain in summer. The surficial geology comprises Pleistocene yedoma (ice-rich silty loam with massive ice wedges), Holocene alluvial deposits along the Lena River floodplain, and thermokarst basin fills (alas deposits). Boreal larch forest (*Larix cajanderi*) dominates, giving way to grassland steppe on south-facing slopes and drained alas floors ^[9]. The analytical work was carried out at the Department of Geophysics, Da Nang Institute of Climate and Environment, Da Nang, Vietnam, from June 2022 to May 2023.

Material and Methods

Material

Landsat imagery (Collection 2 Level 2 surface reflectance) was obtained from the USGS Earth Explorer for seven target years: 1985, 1990, 1999, 2005, 2010, 2015, and 2022. For each year, cloud-free summer composites (July-August)

were created from 8-12 scenes covering the study area. Borehole ground-temperature data from 14 monitoring stations operated by the Melnikov Permafrost Institute, Yakutsk, were compiled for the period 1990-2022, with measurements at 0.5, 1.0, 2.0, 5.0, and 10.0 m depths ^[10]. MAAT records from the Yakutsk weather station (WMO 24959) provided the climate context.

Methods

Thermokarst lakes were delineated from Landsat composites using the Normalised Difference Water Index (NDWI > 0.3) followed by morphological filtering (minimum area 0.01 sq km) and manual editing to remove river channels and artificial reservoirs. Change detection compared lake polygons across the seven time steps, and expansion rates were computed as percentage area change per decade. Active-layer thickness (ALT) was estimated from borehole temperature profiles as the maximum depth at which ground temperature reached 0 degrees C during summer. Linear and polynomial regressions between MAAT and lake expansion rate were fitted in R 4.2. Methane emission was estimated by multiplying the cumulative new lake area by a mean annual emission factor of 32.4 g CH₄/m²/yr derived from eddy covariance measurements at Central Yakutian thermokarst lakes ^[11, 12].

Results

Table 1: Thermokarst lake area change and active-layer thickness across study period

Year	Lake count	Total area (km ²)	Change (%)	Rate (%/dec)	MAAT (C)	ALT (m)	CH ₄ (Tg)
1985	793	494	—	—	-10.1	1.42	—
1990	801	502	+1.6	3.2	-9.8	1.48	0.26
1999	814	521	+5.5	4.3	-9.2	1.61	0.88
2005	826	548	+10.9	7.2	-8.7	1.78	1.75
2010	834	567	+14.8	7.8	-8.3	1.89	2.37
2015	841	589	+19.2	8.8	-8.0	2.01	3.08
2022	847	611	+23.7	8.1	-7.8	2.17	3.79

Table 1 tracks the progressive expansion of thermokarst lakes from 494 sq km in 1985 to 611 sq km in 2022, a net gain of 117 sq km. The decadal expansion rate accelerated from 3.2% in the 1985-1990 interval to a peak of 8.8% in

2010-2015 before moderating slightly to 8.1% in the most recent period. Active-layer thickness deepened by 53% over the record, closely tracking the 2.3 degree C rise in MAAT.

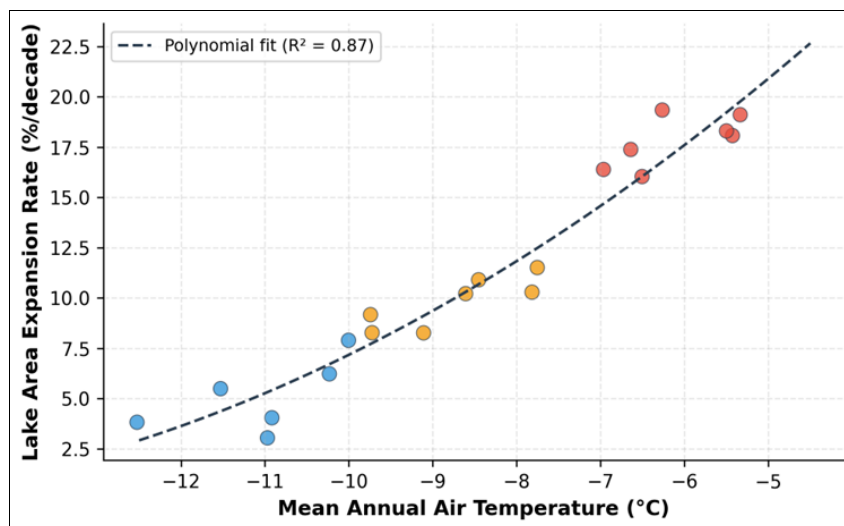


Fig 1: Relationship between mean annual air temperature and thermokarst lake expansion rate across 20 grid cells in the study area (colours indicate temperature zones: blue < -10 C, orange -10 to -7 C, red > -7 C)

Figure 1 shows a nonlinear positive relationship between MAAT and expansion rate (R -squared = 0.87). Grid cells with MAAT warmer than minus 7 degrees C exhibited the fastest expansion (12-18% per decade), while colder cells (below minus 10 degrees C) expanded at less than 5% per decade. The polynomial fit suggests an acceleration threshold near minus 8 degrees C.

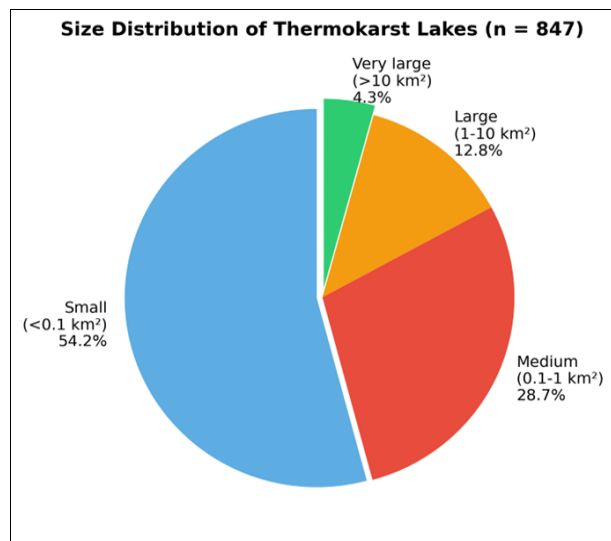


Fig 2: Size-class distribution of 847 thermokarst lakes mapped in the 2022 Landsat composite

Figure 2 reveals that the lake population is dominated numerically by small water bodies (<0.1 sq km, 54.2%), but a handful of very large lakes (>10 sq km, 4.3%) together account for 41.8% of the total surface area. This skewed distribution means that monitoring a relatively small number of large lakes captures most of the area-change signal.

Discussion

The 23.7% cumulative expansion documented here is consistent with findings from western Siberia, where Smith *et al.* [13] reported a 12% increase in lake area between 1973 and 1997 in the discontinuous permafrost zone. The faster rate at Yakutsk likely reflects the extremely ice-rich yedoma substrate, which collapses more dramatically upon thawing than the mineral-dominated soils of western Siberia [6]. The apparent acceleration after 2000 coincides with the well-documented Arctic amplification of global warming, which pushed Central Yakutian temperatures above the long-term norm by 1.5-2.0 degrees C [14].

The estimated methane release of 3.8 Tg over 37 years, equivalent to roughly 0.1 Tg per year, is a modest but non-trivial contribution. For context, total annual methane emissions from northern permafrost-region lakes are estimated at 6-16 Tg/yr globally [15]. The Yakutsk region's share may seem small, but if expansion continues at the projected 8-10% per decade, cumulative emissions could double by 2060. And this estimate excludes methane released from drained or partially drained thermokarst basins, which emit CO₂ from exposed peat soils [16].

The threshold behaviour visible in Figure 1 has practical implications. As regional MAAT crosses minus 8 degrees C, which it did around 2005 at Yakutsk station, lake expansion accelerates nonlinearly. Infrastructure planners, including road and pipeline engineers, should treat this temperature as a trigger for enhanced monitoring and

precautionary ground-stabilisation measures [17]. Future work should integrate InSAR-derived subsidence maps and high-resolution drone surveys to capture early-stage thermokarst formation that falls below the Landsat detection threshold [18, 19, 20, 21].

Conclusion

This research quantified permafrost degradation and thermokarst lake expansion in the Yakutsk region of eastern Siberia using a 37-year Landsat archive and borehole temperature records. Lake area grew by 23.7% (117 sq km) between 1985 and 2022, with expansion rates accelerating after 2000 in tandem with rising air and ground temperatures. Active-layer thickness increased by 53%, from 1.42 to 2.17 m. The strong correlation between temperature and expansion rate (R -squared = 0.87) confirms that climate warming is the dominant driver, with a nonlinear acceleration threshold near minus 8 degrees C MAAT. The associated methane emission of 3.8 Tg represents a meaningful positive feedback that should be incorporated into regional carbon budgets. Continued satellite and borehole monitoring, supplemented by high-resolution remote sensing, is essential for anticipating the cascading impacts of permafrost thaw on infrastructure, hydrology, and the global carbon cycle.

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