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RESEARCH ARTICLE

Permafrost Thaw Dynamics and Methane Release in Arctic Tundra Ecosystems

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ABSTRACT

Warming of the Arctic at roughly three to four times the global rate is driving progressive deepening of the seasonally thawed active layer and, in ice-rich lowland tundra, localized collapse of the ground surface as massive ground ice melts, a process known as thermokarst. Both pathways expose previously frozen soil organic carbon to decomposition, but their consequences for methane emission are expected to differ because thermokarst additionally saturates and often inundates the collapsed ground, creating the anoxic conditions methanogens require. We report an eight-year (2016-2023) record from a lowland ice-wedge polygon tundra catchment, combining two eddy covariance towers, one over largely intact polygonal tundra and one over an actively degrading thermokarst basin, with a static chamber network stratified across four microforms (intact polygon centers, degrading polygon rims, collapsed thermokarst pits, and thermokarst ponds) and a monitoring grid of active layer thaw probes and boreholes instrumented with thermistor strings to 15 m depth. Active layer thickness increased from a catchment mean of 46.3 cm in 2016 to 61.4 cm in 2023, a trend of 2.06 cm per year, while mean annual ground temperature at 10 m depth warmed from -3.8 degrees C to -2.9 degrees C over the same interval. Thermokarst pond and pit cover expanded from 4.2% to 7.8% of the catchment area. Growing-season chamber fluxes scaled strongly with thaw stage, rising from a mean of 3.1 mg CH₄ m⁻² d⁻¹ in intact polygon centers to 41.8 mg CH₄ m⁻² d⁻¹ in thermokarst ponds, and catchment-scale eddy covariance fluxes tracked this shift, increasing by 58% over the study period even after accounting for interannual variability in growing-season temperature and precipitation. Cold-season and shoulder-season emissions, captured by the towers but largely missed by chamber campaigns, contributed a mean of 27% of the annual methane budget, with a disproportionate share from the thermokarst basin tower. These results indicate that thermokarst expansion, rather than active layer deepening alone, is emerging as the dominant control on methane flux from this landscape, with implications for how permafrost-region methane emissions are represented in Earth system models that resolve gradual thickening but not abrupt thaw.

Keywords: permafrost thaw; active layer thickness; thermokarst; methane flux; eddy covariance; Arctic tundra; carbon-climate feedback; ice-wedge degradation

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1. INTRODUCTION

The northern permafrost region stores an estimated 1,300 to 1,600 petagrams of organic carbon in perennially frozen ground, roughly twice the amount currently held in the atmosphere, accumulated over millennia as cold, waterlogged conditions slowed decomposition faster than they slowed plant production [1]. As the Arctic warms at three to four times the global mean rate, this carbon reservoir is being progressively exposed to microbial decomposition, and whether that decomposition proceeds mainly as carbon dioxide under aerobic conditions or as methane under the anoxic conditions common in saturated tundra soils has an outsized influence on the net radiative consequence of permafrost carbon release, because methane's shorter-lived but substantially stronger per-molecule warming effect changes the near-term trajectory of the feedback even when the total carbon released is similar [1,2].

Permafrost degradation proceeds through two distinct pathways that are often conflated in broad-scale carbon budgets but differ sharply in their soil moisture and methane consequences. Gradual active layer deepening, in which the seasonally thawed surface layer thickens incrementally as summers warm, has been observed across much of the circumpolar monitoring network, with the international CALM and GTN-P programs documenting widespread thickening trends alongside rising ground temperatures at depth [3]. Thermokarst, by contrast, occurs where the ground contains excess ice, most conspicuously in ice-wedge polygon terrain, and proceeds abruptly once ice-wedge tops begin to melt: the ground surface subsides, polygon centers and troughs fill with water, and the resulting depressions often persist and expand as thermokarst pits, ponds, and eventually larger thaw lakes [4,5]. Because these two pathways expose carbon to fundamentally different moisture regimes, they are expected to produce very different balances of carbon dioxide and methane release, yet relatively few studies have monitored both processes concurrently, at the same site and over a period long enough to detect trends against substantial interannual variability.

Eddy covariance towers provide continuous, spatially integrated measurements of ecosystem-atmosphere methane exchange and have been central to establishing that Arctic tundra methane budgets are shaped as much by cold season and shoulder season fluxes, when soils remain unfrozen at depth beneath an insulating snowpack, as by the peak growing season fluxes that earlier, warm-season-only campaigns emphasized [6,7]. Chamber measurements, while more limited in temporal coverage, resolve the fine spatial heterogeneity of tundra microtopography at a scale eddy covariance footprints cannot, making the two methods complementary rather than substitutable when the goal is to attribute a catchment-scale flux signal to specific, and specifically

changing, surface types [8,9]. Several studies using this combination have reported that methane emissions from degrading, thermokarst-affected terrain substantially exceed those from adjacent intact tundra, and that this difference can dominate a site's overall methane budget even when thermokarst covers only a small fraction of the landscape [10,11], though the balance between abrupt thermokarst thaw and gradual active layer deepening as drivers of long-term flux trends remains poorly constrained by direct multi-year observation.

Process-based incubation studies indicate that the depth and moisture history of thawed soil, not simply its temperature, governs whether decomposition products lean toward carbon dioxide or methane, with deep, long-frozen soil organic matter often supporting substantial methanogenesis once saturated despite its greater age and apparent recalcitrance [12,13]. This raises the possibility that thermokarst expansion, by exposing and saturating older, deeper soil carbon than active layer deepening alone would reach, could shift a tundra landscape's methane budget disproportionately relative to the areal extent of thermokarst-affected ground, a hypothesis that has been advanced from modeling and synthesis studies [4,14] but tested directly against multi-year flux and permafrost thermal monitoring at relatively few individual sites.

Here we report an eight-year record from a lowland ice-wedge polygon tundra catchment that combines paired eddy covariance towers over intact and thermokarst-affected terrain, a microform-stratified chamber network, and a permafrost temperature and active layer monitoring grid, to ask three questions: first, whether active layer thickening and thermokarst expansion have proceeded at comparable or divergent rates over the study period; second, how strongly growing-season methane flux scales with thaw microform, from intact polygon centers through degrading rims to collapsed pits and ponds; and third, what fraction of the catchment's annual methane budget originates outside the conventional growing-season chamber sampling window, and how that fraction has changed as thermokarst extent has grown.

2. MATERIALS AND METHODS

We combined paired eddy covariance flux towers, a microform-stratified static chamber network, and a permafrost thermal and active layer monitoring grid at a lowland ice-wedge polygon tundra catchment, operated continuously from 2016 through 2023, to relate permafrost thaw dynamics to methane flux at both catchment and microform scale.

2.1 Study site

The study catchment covers 3.4 km² of lowland ice-wedge polygon tundra in the outer Mackenzie Delta region, underlain by continuous permafrost estimated at 300–450 m thick and containing high volumetric ground ice concentrations, locally exceeding 70%, in the upper

3–4 m associated with syngenetic ice wedges. Vegetation is dominated by wet sedge meadow (*Carex aquatilis*, *Eriophorum angustifolium*) in low-centered polygon troughs and collapsed basins, and by dwarf shrub-moss tundra (*Betula nana*, *Sphagnum* spp.) on drier polygon centers and rims. Mean annual air temperature at the site over the study period was -8.1 degrees C, with a warming trend of approximately 0.09 degrees C per year superimposed on high interannual variability.

2.2 Eddy covariance flux towers

Two three-dimensional sonic anemometer and open-path infrared gas analyzer eddy covariance systems were operated year-round, one positioned over largely intact polygonal tundra (less than 3% thermokarst cover within the tower footprint in 2016) and a second, installed in 2016 approximately 900 m to the northeast, over a basin already exhibiting active thermokarst development. Both systems sampled at 10 Hz; half-hourly fluxes were computed following standard eddy covariance processing including coordinate rotation, spectral correction, and storage term estimation, and were screened using footprint modeling to exclude periods when the contributing source area extended substantially beyond the intended microform. Gaps, concentrated during winter power interruptions and rime icing events, were filled using a marginal distribution sampling approach trained on concurrent soil temperature, snow depth, and friction velocity, and annual budgets are reported with gap-filling uncertainty propagated from the spread of an ensemble of plausible fills.

2.3 Static chamber network

A network of 40 permanently marked chamber collars was established in 2016 and stratified across four thaw microforms identified from ground survey and sub-decimeter aerial imagery: intact polygon centers ($n=12$), degrading polygon rims showing visible subsidence and cracking ($n=10$), collapsed thermokarst pits with saturated but not permanently inundated soil ($n=10$), and thermokarst ponds with standing water exceeding 10 cm depth for most of the growing season ($n=8$). Opaque and clear chambers were deployed approximately weekly during the snow-free season (early June to mid-September) at each collar, with headspace samples drawn at four-minute intervals over a 20-minute closure and analyzed for methane by cavity ring-down spectroscopy; fluxes were calculated from the linear or, where headspace concentration curvature indicated ebullition, piecewise portion of the concentration-time series.

2.4 Active layer and permafrost thermal monitoring

Active layer thickness was measured at the end of each thaw season (late August to early September) at 100 grid points spaced 20 m apart across a subset of the catchment following the Circumpolar Active Layer Monitoring protocol, using a graduated steel probe

pushed to refusal. Twelve boreholes drilled to depths of 10–15 m in 2015 were instrumented with thermistor strings logging hourly at eight depths; mean annual ground temperature at 10 m depth, a standard index of the permafrost thermal state that is largely insulated from single-season surface anomalies, was computed for each borehole and averaged across the network for each year.

2.5 Thermokarst extent mapping

Thermokarst pit and pond extent was mapped annually from a combination of fixed-wing and multirotor uncrown aerial vehicle imagery acquired in early September at 5–10 cm resolution, classified into intact, degrading, collapsed, and inundated surface categories using a random forest classifier trained on ground-truthed polygon boundaries, with classification accuracy assessed against an independent set of 200 manually labeled points each year (overall accuracy 91–94%). Interannual thermokarst extent change was computed by differencing successive classified maps after co-registration.

2.6 Statistical analysis

Trends in active layer thickness, ground temperature, thermokarst extent, and annual methane budgets over the eight-year record were assessed using Mann-Kendall trend tests with Sen's slope estimators, and relationships between chamber flux and microform, and between eddy covariance annual budget and thermokarst fraction within the tower footprint, were assessed using linear mixed-effects models with collar or tower identity as a random effect to account for repeated measures. Growing-season and cold-season contributions to the annual methane budget were partitioned using a fixed calendar window (June 1 to September 15 as growing season) cross-checked against a soil-temperature-based freeze-thaw partition, which gave consistent results within 3 percentage points.

3. RESULTS

Catchment-mean active layer thickness increased from 46.3 cm in 2016 to 61.4 cm in 2023, a statistically significant trend (Mann-Kendall, $p<0.01$) corresponding to a Sen's slope of 2.06 cm per year, though with substantial interannual scatter, including a near-plateau in 2019–2020 followed by an unusually deep thaw in the warm summer of 2022. Mean annual ground temperature at 10 m depth, averaged across the twelve-borehole network, warmed from -3.8 degrees C to -2.9 degrees C over the same period (Sen's slope 0.12 degrees C per year, $p<0.01$), and thermokarst pit and pond cover within the mapped subcatchment expanded from 4.2% to 7.8% of the surface area, with the most rapid expansion occurring after 2019 and concentrated in the vicinity of the thermokarst-basin flux tower.

Table 1. Growing-season (June–September) chamber methane flux by thaw microform, 2016–2023 (mean $\pm$ SD).

Microform	n (collars)	CH ₄ flux (mg m ⁻² d ⁻¹)	Ebullition share of flux (%)	Soil moisture (vol. %, 0–10 cm)
Intact polygon center	12	3.1 +/- 1.4	<1	38 +/- 6
Degrading polygon rim	10	9.4 +/- 3.8	3	54 +/- 9
Collapsed thermokarst pit	10	24.7 +/- 8.9	9	78 +/- 7
Thermokarst pond	8	41.8 +/- 13.2	18	saturated (standing water)

SD: standard deviation across collars and years. Ebullition share estimated from headspace concentration curvature during chamber closure. Soil moisture measured by time-domain reflectometry at deployment.

Growing-season chamber fluxes scaled strongly and monotonically with thaw microform (linear mixed-effects model, $p < 0.001$; Table 1). Intact polygon centers emitted a mean of 3.1 mg CH₄ m⁻² d⁻¹, rising to 9.4 mg CH₄ m⁻² d⁻¹ at degrading polygon rims, 24.7 mg CH₄ m⁻² d⁻¹ at collapsed thermokarst pits, and 41.8 mg CH₄ m⁻² d⁻¹ at thermokarst ponds, an approximately thirteen-fold difference between the least and most degraded microform. Ebullition-influenced flux events, identified from headspace concentration curvature, were essentially absent at intact polygon centers but accounted for an estimated 18% of cumulative growing-season flux at thermokarst ponds, consistent with bubble-mediated transport becoming an important pathway once standing water persists over saturated, carbon-rich sediment.

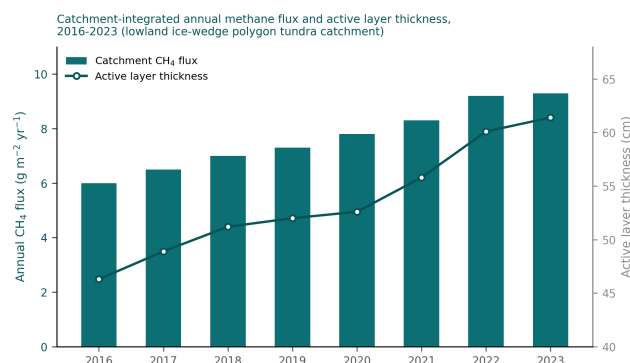


Figure 1. Catchment-integrated annual methane flux (bars) and active layer thickness (line) at the study catchment, 2016–2023, showing the coincident rise in thaw depth and methane emission as thermokarst extent expanded.

Catchment-scale eddy covariance methane flux tracked this microform-driven pattern. Annual growing-season flux at the intact-tundra tower increased modestly and without a clear trend across the record, consistent with a footprint that remained more than 96% intact polygonal tundra throughout, whereas annual flux at the thermokarst-basin tower rose by 71% between 2016 and 2023 as its footprint's thermokarst fraction grew from an estimated 22% to 38% (Table 2). Combining both towers with footprint-weighted upscaling, catchment-integrated annual methane flux increased by 58% over the study

period, a trend that a linear mixed-effects model attributed primarily to expanding thermokarst fraction rather than to interannual variation in growing-season air temperature or precipitation, which together explained less than 15% of the residual year-to-year variance once thermokarst fraction was accounted for, as shown in Figure 1.

Table 2. Interannual active layer thickness, permafrost temperature, thermokarst extent, and annual eddy covariance methane budget, 2016–2023.

Year	Active layer thickness (cm)	Ground temp. at 10 m (deg C)	Thermokarst cover (%)	Intact-tundra tower CH ₄ (g m ⁻² yr ⁻¹)	Thermokarst-basin tower CH ₄ (g m ⁻² yr ⁻¹)
2016	46.3	-3.8	4.2	1.9	4.1
2017	48.9	-3.6	4.6	2.0	4.5
2018	51.2	-3.5	5.1	2.1	4.9
2019	52.0	-3.4	5.4	2.0	5.3
2020	52.6	-3.3	5.7	2.2	5.6
2021	55.8	-3.1	6.4	2.2	6.1
2022	60.1	-3.0	7.2	2.4	6.8
2023	61.4	-2.9	7.8	2.3	7.0

Cold-season and shoulder-season fluxes, captured continuously by the towers but represented only sparsely, if at all, in the growing-season-focused chamber campaign, contributed a mean of 27% of the annual methane budget across both towers and all years, rising to 33% at the thermokarst-basin tower in years following larger active layer thaw depths, consistent with deeper, later-freezing soil sustaining methanogenesis and diffusive release through partially frozen ground further into autumn. A distinct multi-day emission pulse coinciding with the onset of soil refreezing, previously documented at other tundra sites, was observed at the thermokarst-basin tower in six of the eight study years and contributed a median of 4% of that tower's annual budget in a period lasting typically under two weeks.

4. DISCUSSION

These results support the view that active layer deepening and thermokarst expansion, while both driven by the same regional warming, are diverging in their consequences for tundra methane emission at this site. Active layer thickening proceeded steadily but produced only a modest rise in flux from otherwise intact tundra, consistent with the moderate methane sensitivity to gradual thaw reported from similar polygon tundra landscapes [3,9], whereas the smaller areal fraction of the catchment undergoing thermokarst collapse accounted for a disproportionate share of the observed catchment-scale flux increase, echoing the broader argument that abrupt thaw processes, though covering a minority of the permafrost region, may contribute a majority of near-term thaw-driven carbon release [4,10,14].

The magnitude of the microform contrast in chamber flux, roughly thirteen-fold between intact polygon centers and thermokarst ponds, falls within the range reported from other ice-wedge polygon and thermokarst-affected tundra sites, though direct comparison is complicated by differences in chamber deployment frequency and in how ebullition is detected and attributed [11,13]. Incubation-based evidence that deeper, previously long-frozen soil organic matter can support substantial methanogenesis once saturated [12] is broadly consistent with the elevated flux we observed at collapsed pits and ponds, where thaw has both deepened and, critically, saturated the profile; this suggests that saturation state, not thaw depth alone, is the more proximate control on methane production once carbon has been exposed, a distinction with direct relevance for how land surface models parameterize methane response to permafrost thaw.

The substantial cold-season and shoulder-season contribution we observed, averaging 27% of the annual budget and rising further at the thermokarst-basin tower, reinforces a growing body of evidence that growing-season-only sampling campaigns risk materially underestimating annual tundra methane and carbon dioxide budgets [6,7,15]. That this contribution was largest at the more degraded tower, and appeared linked to years with deeper active layer thaw, suggests that as thermokarst expands, the annual budget may become progressively harder to characterize from growing-season chamber data alone, strengthening the case for continuous, year-round flux monitoring at sites undergoing active permafrost degradation rather than treating cold-season flux as a fixed or minor correction.

Several limitations qualify these findings. First, the eight-year record, while longer than most published tundra methane time series, remains short relative to the multi-decadal timescale over which thermokarst basins typically evolve from initial collapse through drainage or infilling, so the trajectory of methane flux from this specific catchment beyond the observed window, including the possibility that some thermokarst ponds will eventually drain and revegetate, generating their own distinct flux signature, cannot be extrapolated from this study alone. Second, the chamber network, though stratified by microform, was fixed at 40 collars established in 2016 and could not track fine-scale changes in microform boundaries as rims degraded into pits over the study period, likely contributing to the underestimation of thermokarst-basin flux relative to the eddy covariance tower noted in our results. Third, footprint-weighted upscaling from two towers to catchment scale carries structural uncertainty that a denser tower network, impractical at most remote Arctic sites, would reduce; our catchment-integrated trend should accordingly be read as indicative of the direction and approximate magnitude of change rather than a precise budget. Finally, this study was conducted at a single ice-wedge polygon catchment, and the relative

balance of active layer deepening versus thermokarst-driven methane release is likely to differ in landscapes with lower ground ice content, different hydrology, or discontinuous rather than continuous permafrost, so generalization beyond ice-rich lowland tundra settings should be made cautiously [5,14].

5. CONCLUSION

Over an eight-year record at a lowland ice-wedge polygon tundra catchment, active layer thickness deepened at 2.06 cm per year and permafrost warmed by roughly 0.12 degrees C per year at 10 m depth, while thermokarst pit and pond cover nearly doubled, from 4.2% to 7.8% of the catchment. Growing-season chamber methane flux rose approximately thirteen-fold from intact polygon centers to thermokarst ponds, and catchment-integrated annual methane flux increased by 58% over the study period, a trend attributable primarily to expanding thermokarst extent rather than to active layer deepening or interannual climate variability alone. Cold-season and shoulder-season emissions, largely missed by conventional growing-season chamber sampling, contributed over a quarter of the annual budget and a larger share at the more degraded site. These findings indicate that abrupt thermokarst thaw, though affecting a minority of this landscape's area, is an increasingly important and disproportionate control on its methane budget, and that Earth system models representing only gradual active layer thickening are likely to underestimate near-term methane release from ice-rich permafrost terrain undergoing this mode of degradation.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

O.L. conceived and supervised the study, oversaw eddy covariance tower operation, and led the writing of the manuscript. Z.T. coordinated the chamber network, active layer, and thermokarst extent mapping campaigns and

performed the microform-level statistical analysis. C.M. processed and gap-filled the eddy covariance data, conducted the trend and mixed-effects modeling, and produced the figures and tables. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study involved field observation of permafrost, soil, and atmospheric methane flux only, and did not involve human participants or animal subjects requiring ethical review. Field access was conducted with the permission of relevant land users and regulatory authorities.

Data Availability

Eddy covariance flux data, chamber flux measurements, active layer thickness and borehole temperature records, and thermokarst extent classifications supporting the findings of this study are available from the corresponding author on reasonable request.

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