https://doi.org/10.5194/egusphere-2026-3394
Preprint. Discussion started: 16 November 2026
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CaMPground 1.0: A simple soil temperature model for integrating permafrost dynamics into large-scale peatland carbon models

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Key words: permafrost, modelling, carbon, Hudson Bay Lowlands, ground temperature

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https://doi.org/10.5194/egusphere-2026-3394
Preprint. Discussion started: 16 November 2026
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Abstract

Permafrost-affected peatlands represent 34 Mha or 31 % of Canada's peatlands. Estimations of carbon (C) emissions and removals from Canadian peatlands are incomplete without knowing the contributions from these permafrost-affected areas. Currently, the Canadian Model for Peatlands (CaMP) does not account for permafrost as it cannot simulate active layer thickness (ALT) to determine the proportion of thawed versus frozen peat. Additionally, although the numerical Northern Ecosystem Soil Temperature (NEST) model predicts temperature and ALT accurately in the Hudson Bay Lowlands (HBL), it is too computationally intensive to be fully integrated within CaMP. Therefore, to integrated permafrost dynamics into CaMP and for carbon peatland models overall, we calibrated a simple sinusoidal model, known as CaMPground, which can estimate ground temperature at multiple depths on annual to sub-annual timescales. The model was validated for four peatland classes based on nutrient type and permafrost (bog, fen, permafrost fen, and permafrost bog) within the HBL. The model was tested for permafrost and non permafrost sites as the initial step in developing a vertically resolved version of CaMP, tracking carbon movement between soil layers. The model performed well for both permafrost and non permafrost classes, producing the lowest root mean square error (RMSE) for fens and permafrost fens monthly (1.8 and 1.6 °C, respectively). However, the model produced the highest error for permafrost bogs monthly (2.3 °C) likely due to the lack of freeze/thaw dynamics, leading to increased error at sites with a substantial zero-curtain effect. Despite this limitation, the errors for CaMPground were comparable to NEST (RMSE of 2.1 and 2.6 °C, respectively). Ground temperatures generated by the model will be used to determine annual ALT within a modified version of CaMP to simulate carbon dynamics in Canadian permafrost peatlands, improving carbon emission estimates in Canada.

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1. Introduction

The Canadian Model for Peatlands (CaMP) is used within the International Panel for Climate Change's reporting framework to quantify emissions and removals associated with land-use change and management of peatlands in Canada. Although CaMP has successfully modelled carbon fluxes within Canada's non-permafrost peatlands (Bona et al., 2024), modelling in permafrost peatlands is complicated due to the presence of thawed and frozen peat that cycle carbon differently. However, permafrost peatlands are abundant in Canada, spanning around 23 Mha in the Hudson Bay Lowlands (HBL) and storing an estimated 27 Pg C (Bona et al., 2024; Li et al., 2025). To accurately assess carbon pools and fluxes in permafrost peatlands using CaMP, ground temperature profile and active layer thickness (ALT) must be incorporated to account for the amount of carbon which remains "locked" in the permafrost versus the thawed proportion available for decomposition and lateral export (Olefeldt & Roulet, 2014; Jones et al., 2016; Estop-Aragonés et al., 2018; Heffernan et al., 2020; Hugelius et al., 2020; Treat et al. 2021). Most simple ALT models utilize edaphic parameters, requiring at least some geophysical measurements, which can be sparse in remote permafrost regions (Bonnaventure and Lamoureux, 2013; Peng et al., 2023; Uxa et al., 2026). Alternatively, ALT can be predicted using ground temperature observations, which are more commonly measured and modelled in remote permafrost environments (Romanovsky et al., 2010; Biskaborn et al., 2015, 2019; Muir et al , 2025; Uxa et al., 2026).

Ground temperature is influenced by a number of local and regional factors which moderate the transfer of heat into and out of the ground. During the freezing season, ground temperatures are primarily influenced by snow cover, which limits heat loss (Henry & Smith, 2001; Smith & Riseborough, 2002; Zhang, 2005). In the absence of vegetation, topography is the main control

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on snow redistribution, and where vegetation is present, snow can be trapped by shrubs or intercepted by taller vegetation (Smith, 1975; Young et al., 1997; Zhang et al., 2005). During the thawing season, vegetation impacts ground temperatures by restricting incoming solar radiation at the ground surface through shading, evapotranspiration, and differences in albedo (Smith, 1975; Smith & Riseborough, 2002; Chasmer et al., 2011; Chang et al., 2015; Porada et al., 2016). Ground temperatures are also influenced by thermal conductivity of the surficial materials, specifically the difference in thermal conductivity between frozen and unfrozen states, which is dependent on soil moisture and organic (i.e., peat) content (Goodrich, 1982; Smith & Riseborough, 1996, 2002; Westermann et al., 2015; Way & Lewkowicz, 2016). As such, spatial ground temperature models often assign empirical parameters representing these temperature influences based spatial attributes such as landcover (Riseborough et al., 2008; Gisnås et al., 2013; Westermann et al., 2015; Way & Lewkowicz, 2016; Obu et al., 2019; Vegter et al., 2024).

Many types of ground temperature models exist, ranging from complex numeric energy balance simulations to more simplistic analytical models. The Northern Ecosystem Soil Temperature model (NEST) is a numerical model developed to predict ground temperatures at 30-minute intervals at incremental depths, with increments ranging from 0.1 m near the surface to 4.8 m at 119.75 m depth (Zhang et al., 2003). NEST performs well in permafrost regions across Canada (Chen et al., 2003; Zhang et al., 2006; Zhang et al., 2015; Way et al., 2018; Wang and Way, 2025), including in two regions within the HBL (Zhang et al., 2012; Zhang, 2013; Ou et al., 2016a; Ou et al., 2016b). However, it requires a large amount of daily input data and computational resources, which makes it too complex to be fully integrated within an operational, annual time-step peatland C cycle model like CaMP.

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In contrast, seasonal variation of soil temperature has also been described using a simple sinusoidal function that has the potential to predict ground temperature and annual active layer thickness across different peatland classes. This function estimates seasonal temperature variation as a sine wave that oscillates around an average temperature, with decreasing wave amplitude and delayed timing of peak temperatures with depth. This analytical solution of the heat conduction equation operates under an ideal boundary and ground condition (i.e., land surface temperature follows a sine function, thermal properties are uniform and constant, and no latent heat for soil thawing and freezing). Although the function is relatively simple, it can simulate variation of temperatures with time at user defined depths. Several studies ranging across of variety of landscapes and climate conditions have utilized this function to model annual and daily ground temperature fluctuations with depth (Elias et al., 2005; Weiss et al., 2006; Holmes et al., 2008; Droulia et al., 2009; Woo et al., 2012). However, this function has yet to be used with in larger carbon accounting models or even widely utilized spatially (most studies simulated soil temperature profiles at individual sites). To use the function spatially, soil thermal parameters need to be empirically linked to a proxy spatial attribute. As the differences in peat characteristics (e.g., peat density and moisture regime) among bogs, fens, and permafrost bogs impact soil thermal response, peatland class can serve as this proxy (Bridgham et al., 1999; Connon et al., 2014; Jean & Payette, 2014; Muir et al. 2025).

This study aims to develop and test a simple sinusoidal ground temperature model to predict ground temperature and annual ALT across different four peatland classes: bog, fen, permafrost bog, and permafrost fen. We tested the model using observed data from across Northern Canada to verify its performance within peatlands across permafrost zones. Model results were also compared to the NEST model to assess the effectiveness of this simple methodology. By

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capturing annual frozen peat and ALT, the model will provide a scalable solution for predicting peatland carbon fate in large-scale regional to national models such as CaMP.

2 Methods

2.1 Study Area and Data Sites

Sites with ground temperature observations at a variety of peatland classes across Canada and the United States were used to calibrate and validate the model (Figure 1). These sites consisted of preexisting datasets, established and maintained by several Canadian University and Government partners. A total of 68 sites were used, with data records ranging from 1 to 9 years (Table 1). As the primary objective was development of a ground temperature model specifically for integration in peatland carbon accounting, data sites were concentrated in peatlands, with primary focus on the HBL (the initial test site of a larger carbon accounting study). However, due to limited data in this location, we also utilized data for peatland sites outside of the HBL. Annual ground surface temperatures ranged from -2.6 to 7.0 °C. Within the HBL, annual ground surface temperatures ranged from -2.6 to 6.3 °C and ALTs ranged from 40 to 195 cm.

In alignment with the CaMP model peatland classes and as all were underlain by peat, sites were divided into 4 classes (bog, fen, permafrost bogs, and permafrost fens) based on typical vegetation and nutrient status (as defined in Table 1 and Bona et al., 2020) and permafrost presence/absence. Although permafrost presence in fens is uncommon, based on previous observations (Zoltai and Tarconai, 1974) and peat core datasets (Bauer et al., 2024; Kolari and Garneau, unpublished), permafrost can be present in sites classified as fens. However, these features are likely only present within continuous permafrost and within relatively dry fens (Dyke and Sladen, 2010). It is also possible that when representative vegetation (i.e., sedges) is

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Preprint. Discussion started: 16 November 2026
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used as the main classification criteria, what we refer to as permafrost or frozen fens, that occur in northern parts of HBL, may actually be permafrost sedge meadows. However, to fit these features within a peatland classification framework, we elect to refer to them as permafrost fens within this study.

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Preprint. Discussion started: 16 November 2026
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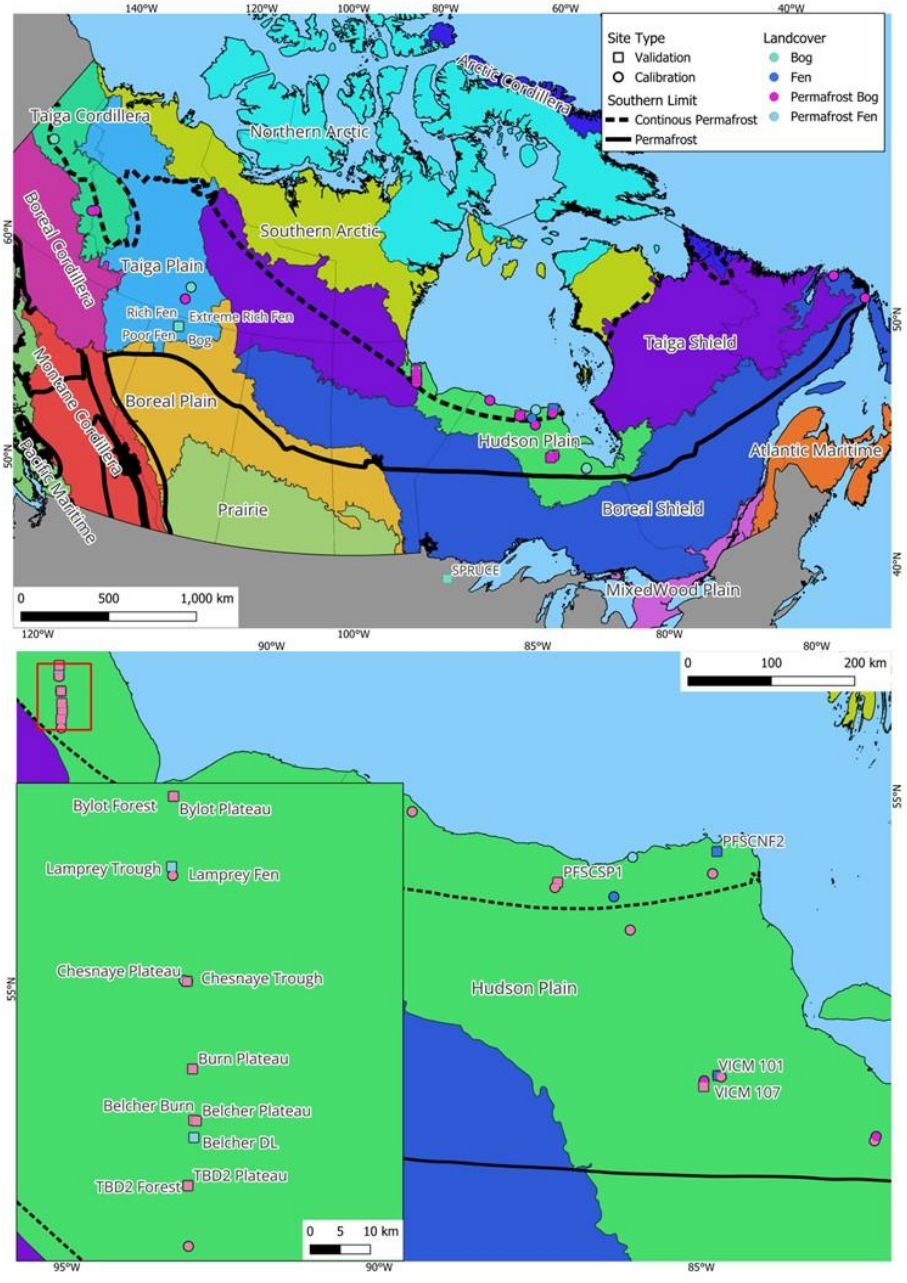


Figure 1. Map showing the location of the model calibration and validation sites. Validation site names are given. Permafrost extent modified from Brown et al. (2002). Contains information licenced under the Open Government Licence—Canada and information from the United States Census Bureau.

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Peatland sites were split into calibration and validation data sets based on location and record length. Sites with longer data records and more sampling depths were typically selected for calibration. During calibration, individual months and depths were treated as observations. As a result, a greater number of calibration sampling points were potentially generated from a smaller number of sites for the fen and bog classes. Validation sites were primarily located in the HBL, except for the bog and fen classes, where an additional bog and three fen sites from northern Alberta were included. The model was also validated against six bogs sites in northern Minnesota to assess the performance of the model in a non-permafrost environment.

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Preprint. Discussion started: 16 November 2026
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Table 1. Number of sites, record lengths and sampling depths for the calibration and validation sites in each peatland class. General vegetation characteristics of each class is also provided.

Peatland Class	Calibration Sites			Validation Sites			Description	Data Sources
	Sites	Record Lengths (yr)	Sampling Depths (m)	Sites	Record Lengths (yr)	Sampling Depths (m)		
Bog	4	2 - 9	0.1 - 1	2 *6	1 – 7	0.05 – 1 *0.05 - 2	Dominated by *Sphagnum* moss. Potentially have black spruce trees. Receive water solely from precipitation, fog, or snow melt. Peat > 40 cm	Barreto, C. (2010 – 2018). [Ground temperature data, Ontario] [Unpublished Data]. Ontario Ministry of Natural Resources. Bonnaventure, P.P. (2015 – 2021). [Ground temperature data, Yukon] [Unpublished Data]. University of Lethbridge Holloway, J. E., Wang, Y., Lewkowicz, A. G., Wolfe, S. A., Turetsky, M. R. & Baltzer, J. L. (2026). Field observations of climate, soil, and ecological conditions within the first five years following wildfire, southern Northwest Territories. Geological Survey of Canada, Open File, 9299e, 23. Natural Resources Canada. https://doi.org/10.4095/pzyenpg5r0 Kempton, K. E. (2025). Greenhouse Gas Fluxes Along a Trophic Gradient in Thermokarst Wetlands (Master's Thesis, University of Alberta).

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								Hanson, P.J., J.S. Riggs, C. Dorrance, W.R. Nettles, and L.A. Hook. (2015). SPRUCE Environmental Monitoring Data: 2010-2016. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.001
Fen	2	5 - 9	0.1 - 2	4	1 - 4	0.25 - 2	Dominated by graminoids, dominated by bryophytes, or contain a mixture of both. Water sourced from ground water or runoff. Peat > 40 cm	Barreto, C. (2010 – 2018). [Ground temperature data, Ontario] [Unpublished Data]. Ontario Ministry of Forests. Brown, G. (2018 – 2021). [Ground temperature data, Ontario] [Unpublished Data]. Ontario Ministry of Natural Resources. Kempton, K. E. (2025). Greenhouse Gas Fluxes Along a Trophic Gradient in Thermokarst Wetlands (Master's Thesis, University of Alberta).
Permafrost Bog	15	1 - 7	0.1 - 3	12	1 - 3	0.05 - 2	Palsas and peat plateaus underlain by permafrost. Forested palsas are covered in dense black spruce trees with *Sphagnum* and feather moss. Non-forested palsas are dominated by	Barreto, C. (2010 – 2018). [Ground temperature data, Ontario] [Unpublished Data]. Ontario Ministry of Natural Resources. Bonnaventure, P.P. (2015 – 2021). [Ground temperature data, Yukon] [Unpublished Data].

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							dwarf birch and lichen. Peat > 40 cm	University of Lethbridge. Brown, G. (2018 – 2021). [Ground temperature data, Ontario] [Unpublished Data]. Ontario Ministry of Natural Resources. Holloway, J. E., Wang, Y., Lewkowicz, A. G., Wolfe, S. A., Turetsky, M. R. & Baltzer, J. L. (2026). Field observations of climate, soil, and ecological conditions within the first five years following wildfire, southern Northwest Territories. Geological Survey of Canada, Open File, 9299e, 23. Natural Resources Canada. https://doi.org/10.4095/pzyenpg5r0 Rahman, T. & Roy-Léveillée, P. (2022 – 2024). [Ground temperature data, Manitoba] [Unpublished Data]. Université Laval. Way, R.G., Lewkowicz, A.G., and Zhang, Y. 2018. Characteristics and fate of isolated permafrost patches in coastal Labrador, Canada. The Cryosphere, 12(8): 2667–2688. doi:10.5194/tc-12-2667-2018.
Permafrost Fen	3	1 - 3	0.5 – 1.5	2	1	1	Underlain by permafrost. Dominated by	Brown, G. (2018 – 2021). [Ground temperature data, Ontario] [

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							graminoids, dominated by bryophytes, or contain a mixture of both. Water sourced from ground water or runoff. Peat > 40 cm	Unpublished Data]. Ontario Ministry of Natural Resources Rahman, T. & Roy-Léveillée, P. (2022 – 2024). [Ground temperature data, Manitoba] [Unpublished Data]. Université Laval.

* Six bog sites from Northern Minnesota which are included as a separate analysis. The inclusion of this dataset did not impact the record lengths for validation bogs.

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2.2 Data Collection

Ground temperature data were collected in slightly different ways among the studies. Typically, ground surface temperature and at least one ground temperature at depth were recorded at 1 to 2-hour intervals at each site. Temperature was recorded using thermocouple sensors including: Hobo U23-002 (accuracy ± 0.23 °C), Hobo U23-003 (accuracy ± 0.21 °C), Hobo U12-013 (accuracy: ±0.35°C), Cambell Scientific 107 temperature probe (accuracy ± 0.2°C), 44033RC Precision Thermistor (accuracy ± 0.1 °C), Hobo Pendant MX2201 (accuracy ± 0.5 °C), Cambell Scientific CS225 (accuracy ± 0.2 °C) or a RBR (accuracy 0.002 °C) temperature logger. Ground surface temperature was measured 2-5 cm below the ground surface. At most sites, ground temperatures were measured at multiple depths (0.1 to 2.5 m), and ALT was determined by interpolating the maximum depth of thaw (0 °C) between sensors. In the remaining sites (13 permafrost bogs and four permafrost fens in the Northern Manitoba HBL) ground temperature was only measured at one depth (typically 1 m) and ALT was determined by physical probing near the end of the thawing season. Annual average temperatures at a majority of sites were calculated using a calendar year, however for sites without a full calendar year of data (n = 13) a hydrologic year (Sep -Aug) was used to maximize the number of sites.

2.3 Model Description

To model monthly ground temperature at depth, we selected a first order harmonic wave function, due to its simplicity and ability to predict monthly temperature at user defined depths. The function predicts monthly temperature along the soil profile as

$$T_{m,z} = (T_s - (\frac{A}{b} * e^{-\frac{z}{d}}) * \sin(\frac{\pi * m}{6} - \frac{Z}{d} + P) \quad \text{(Eq 1)}$$

where,

$T_{m,z}$ is the monthly mean temperature (K) at depth (z)

https://doi.org/10.5194/egusphere-2026-3394
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T_s is the annual mean temperature (K) at the ground surface
z is depth (m)
A is the peak to peak monthly temperature amplitude at the ground surface (K)
b is the amplitude modifier (typically 2) (unitless)
d is the damping depth (m)
m is the month (1-12 for January to December)
P is the period modifier (unitless)

In this form, the model assumes that T_s remains constant. In permafrost environments, however, annual average temperature decreases through the active layer (reaching its minimum at the top of permafrost) due to the seasonal variability in heat conduction (Goodrich 1978; Burn & Smith, 1998, Romanovsky & Osterkamp, 1995; Smith & Riseborough, 2002). The rate of this cooling is often exponential, with greater changes in temperature closer to the ground surface (Figure S2) (Burn & Smith, 1998). Therefore, the assumption of constant annual temperature with depth does not hold true in permafrost environments. To be more representative of in situ conditions, we modified the first order harmonic model (sine function) to incorporate annual average temperature cooling with depth.

Assuming constant thermal properties with depth, the modified harmonic equation (referred to as CaMPground) is

$$T_{m,z} = (T_s * e^{-kz}) - (\frac{A}{b} * e^{-\frac{z}{d}}) * \sin(\frac{\pi * m}{6} - \frac{Z}{d} + P) \quad \text{(Eq 2)}$$

where k is a parameter (m^{-1}) for the decay of the annual mean temperature with depth.

2.4 Parameter Calibration

Reference parameter values for the annual temperature decay with depth (k) and the damping depth (d) were calculated using the measured temperatures at the calibration sites and Equations 3 and 4.

https://doi.org/10.5194/egusphere-2026-3394
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$$k = \frac{\ln(\frac{T_1}{T_2})}{z_2 - z_1}$$ (Eq 3)

where T_1 and T_2 are the annual mean temperatures at two different depths (z_1 and z_2)

$$d = \frac{z_1 - z_2}{\ln(\frac{A_1}{A_2})}$$ (Eq 4)

where A_1 and A_2 is the peak to peak temperature amplitudes at two different depths (z_1 and z_2). We then used Bayesian inversion to calibrate k, d, the peak-to-peak monthly amplitude modifier (b), and the period modifier (P) for four peatland classes (bog, fen, permafrost bogs, and permafrost fen). The Bayesian inversion framework can be expressed as

$$p(c|Z) = a \times p(Z|c) \times p(c)$$ (Eq 5)

where $p(c|Z)$ is a posterior probability density function of parameters c; $p(Z|c)$ is a likelihood function of parameters c; $p(c)$ is a prior probability density function of parameters c; and a is a normalization constant (Mosegaard and Sambridge, 2002). Assuming that the prediction errors are uncorrelated and have a Gaussian distribution, the likelihood $p(Z|c)$ can be expressed as

$$p(Z|c) = \exp\left\{-\sum_{i=1}^{N} \frac{(x_i - z_i)^2}{2\sigma^2}\right\}$$ (Eq 6)

where x_i is the ith modelled temperature value; z_i is the ith observed temperature value; σ^2 is the error variance, which we assume to be equal to the variance in the observed ground temperatures; and N is the number of ground temperature observations.

The prior distributions for the parameters were assumed to be uniform. We sampled from the posterior parameter distribution $p(c|Z)$ by proposing a set of parameters and accepting or rejecting it using the Metropolis criterion (Spall, 2005). Because the prior parameter distribution

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Preprint. Discussion started: 16 November 2026
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was assumed to be uniform, we proposed new parameter sets, c^{new}, using a uniform proposal distribution:

$$c^{new} = c^{k-1} + r \times \frac{c^{max} - c^{min}}{D} \quad \text{(Eq 7)}$$

where c^{k-1} is the set of parameters accepted at simulation step k-1; c^{max} and c^{min} are upper and lower bounds of the parameters; r is a random number in the range [-0.5, 0.5]; and D = 5. Once the new set of parameters was generated, we calculated the probability of its acceptance as:

$$P(c^{new}|c^{k-1}) = min\left\{1, \frac{P(Z|c^{new})}{P(Z|c^{k-1})}\right\} \quad \text{(Eq 8)}$$

and compared the value of $P(c^{new}|c^{k-1})$ with a random number U drawn from a uniform distribution within a range [0, 1]. If U≤ $P(c^{new}|c^{k-1})$, c^k was set to c^{new}, otherwise c^k was set to c^{k-1}. We repeated this procedure 5,000 times to generate a covariance matrix C_0, and then switched the parameter proposal distribution to the multivariate normal as in Xu et al. (2006) for the next 295,000 simulations:

$$c^{new} = N(c^{k-1}, C_k) \quad \text{(Eq 9)}$$

Where C_k is defined as in (Haario et al., 2001):

$$C_k = \begin{cases} C_0 & k = 5000 \\ s_d cov(c^0, \dots, c^{k-1}) & k > 5000 \end{cases} \quad \text{(Eq 10)}$$

Where s_d = 2.38/$\sqrt{n}$, and n is the number of parameters being estimated (Gelman et al., 1996). We discarded the first half of the accepted parameters as a "burn-in" period, and the second half of the accepted parameters to generate the marginal posterior parameter distributions and calculate the average parameter values, which were used in the ground temperature model (eq. 2) (Table S2). The calibrated parameters were similar to those previously reported (or calculated

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from reported temperatures) for other peatlands in North America, Finland, and Russia (Table S2) (Nichols, 1998; Weiss et al., 2006; Friesen et al., 2021; Roudina et al., 2025).

2.5 Active Layer Thickness Estimation

To estimate the active layer depth (at permafrost fens and permafrost bogs) we numerically solved the inequality $T(z,m) < 273.15\ K$ to identify depths at which ground temperatures were below freezing. This inequality can also be rewritten as

$$f(z) = T_s e^{-kz} - \frac{A}{b} e^{\frac{-z}{d}} \sin\left(\frac{\pi * m}{6} - \frac{Z}{d} + P\right) - 273.15 < 0 \quad \text{(Eq. 11)}$$

For a depth range of 0-20 meters, we evaluated $f(z)$ on a dense depth grid. To ensure that narrow freezing intervals were not missed, we used a minimum of 25 grid points per oscillation period, with additional refinement as needed. Sign changes in $f(z)$ between adjacent grid points were used to bracket roots, or depths where $T(z,m) = 273.15\ K$. Each bracketing interval was then refined using a one-dimensional root-finding algorithm (bisection as implemented in uniroot function in R (R Core Team, 2024) to determine root location with a tolerance of 10^{-10}. The refined roots partition the depth range into sub-intervals. For each sub-interval, the sign of $f(z)$ was evaluated at the midpoint to determine whether the inequality $f(z) < 0$ was satisfied throughout that interval. To avoid numerical overflow at large depths or extreme parameter values, exponential terms were evaluated using bounded exponentials.

This procedure was repeated for each month between May and October. For each month, the minimum depth at which temperatures were below freezing was recorded. We then found the maximum of these minimum freezing depths across this six-month period and set it as the active layer depth for the given grid cell in a given year. CaMPground ALTs were compared to

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observed ALTs and modelled ALTs from the European Space Agency (ESA) which is estimated using satellite and reanalysis data to drive a transient permafrost model (Westermann et al., 2025) and NEST at the validation sites within the HBL.

3 Results

3.1 Model Performance in Northern Peatlands

For the validation sites, CaMPground results showed good agreement with ground temperature observations at monthly and annual time scales across peatland classes and depths. For all peatland classes and depths, the model produced a low root mean square error (RMSE) and high r^2, performing slightly better at an annual than monthly scale (Figure 2). The model simulated slightly warmer temperature on both annual and monthly scales across all peatland classes (warm bias of 0.5 ºC for both) and showed increased error at around 0 °C. Based on peatland class, the model produced the lowest error for the two fen classes (monthly) and bog classes (annually) and had the highest error for permafrost bogs on a monthly and annual scale. The model underpredicted temperatures for the warmest bogs and simulated warmer conditions for the coldest permafrost bogs.

https://doi.org/10.5194/egusphere-2026-3394
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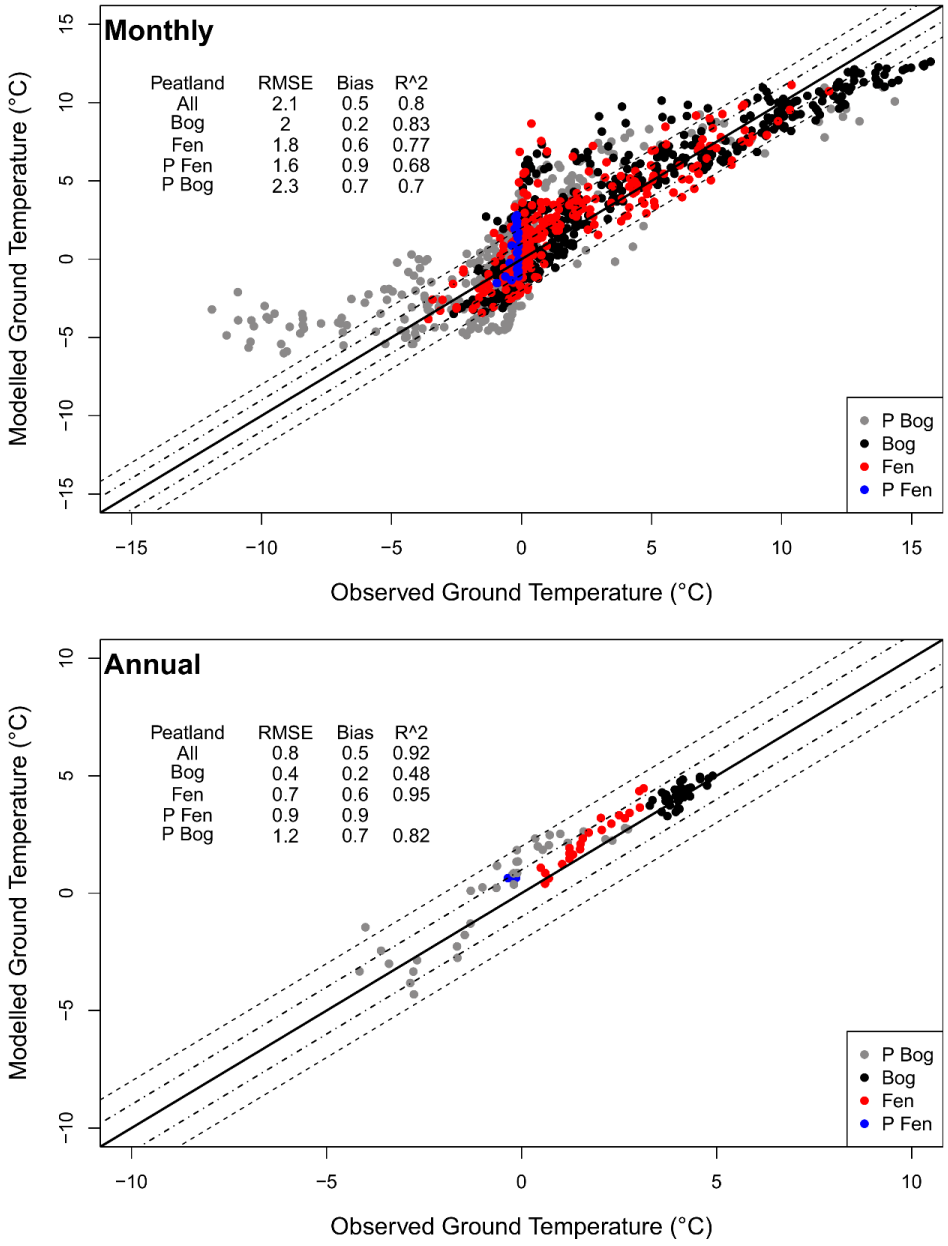


Figure 2. Scatter plots of the modelled ground temperature compared to the observed ground temperature at various depths for A) monthly and B) annual time periods. Solid black line shows the 1:1 ratio while the dashed lines indicate 1 and 2 ºC temperature error. Root mean square error (RMSE) and bias are given in °C. No r^2 is given annually for permafrost fen (P Fen) as there were only two observations.

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The model performance improved with depth on a monthly scale for all validation sites and for each peatland class (Table 2). However, there was more variation in annual model performance based on depth. The model had the lowest error at 0.5 m overall and for the bog class, annually, and lowest error fens and permafrost bogs for depths greater than 1m. The permafrost bog class also had low error for depths less than 0.5 m. For permafrost bog class and for all sites combined, CaMPground produced the greatest error (annually) at 1 m and greatest error for fens and bogs at depths less than 0.5 m. However, the maximum error for each depth and peatland remained relatively small, with a maximum RMSE of 2.5 °C monthly and 1.3 °C annually. The model also produced a positive bias (model overpredicted temperature) for all peatland classes and depths except the bog class at 1.0 m where there was a negative bias (model underpredicted temperatures).

Table 2. Monthly and [annual] root mean square error (RMSE) and bias for different depths (or depth range) for the validation set overall and based on peatland class. The number of depths with observations (n) overall and for each peatland class are given. A positive bias indicated modelled temperatures were warmer than the observed.

Depth (m)	All		Bog		Fen		Permafrost Fen		Permafrost Bog	
	RMSE (°C)	Bias (°C)	RMSE (°C)	Bias (°C)	RMSE (°C)	Bias	RMSE (°C)	Bias (°C)	RMSE(°C)	Bias (°C)
0.0-0.5	2.4 [0.7] (n = 12)	0.5 [0.5]	2.3 [0.4] (n = 4)	0.3 [0.4]	2.5 [1.0] (n = 3)	0.9 [0.9]			2.5 [1.1] (n = 5)	0.6 [0.5]
0.5	2.0 [0.3] (n = 8)	0.5 [0.5]	1.6 [0.2] (n = 2)	0.4 [0.1]	2.2 [0.9] (n = 4)	0.7 [0.9]			2.1 [1.2] (n = 2)	0.4 [0.8]
1.0	2.0 [1.0] (n = 15)	0.6 [0.6]	0.9 [0.4] (n = 1)	-0.3 [-0.3]	1.4 [0.5] (n = 1)	0.5 [0.5]	1.6 [0.9] (n = 2)	1.2 [0.9]	2.4 [1.3] (n = 11)	0.6 [1.0]
> 1.0	1.7 [0.8] (n = 6)	0.1 [0.1]			1.2 [0.4] (n = 2)	0.2 [0.1]			2.0 [1.1] (n = 4)	0.1 [0.1]

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For individual validation sites, the model showed variability in performance, with low error for some sites and larger errors for others (Figure 3). The best performing observation was for a permafrost bog near Victor Mine in the Ontario HBL at 2 m (Figure 3 A). Interestingly, this site also had one of the four poorest model performances at 0.35 m (Figure 3 H). The other three observations with the lowest model errors were in a bog also located near Victor Mine in the Ontario HBL at 1 m (Figure 3 B), a permafrost bog in the northern Manitoba HBL at 1 m (Figure 3 C), and a fen in the Ontario HBL at 2 m (Figure 3 D). The remaining three observations with the poorest model performance were two permafrost bogs (Figure 3 E and F) located in the northern Manitoba HBL (a 1 m depth) and a fen located at Lutose, AB at 0.25 m (Figure 3 G). Time series plots for the remaining validation sites can be found in the Supplemental Data (Figure S1-4).

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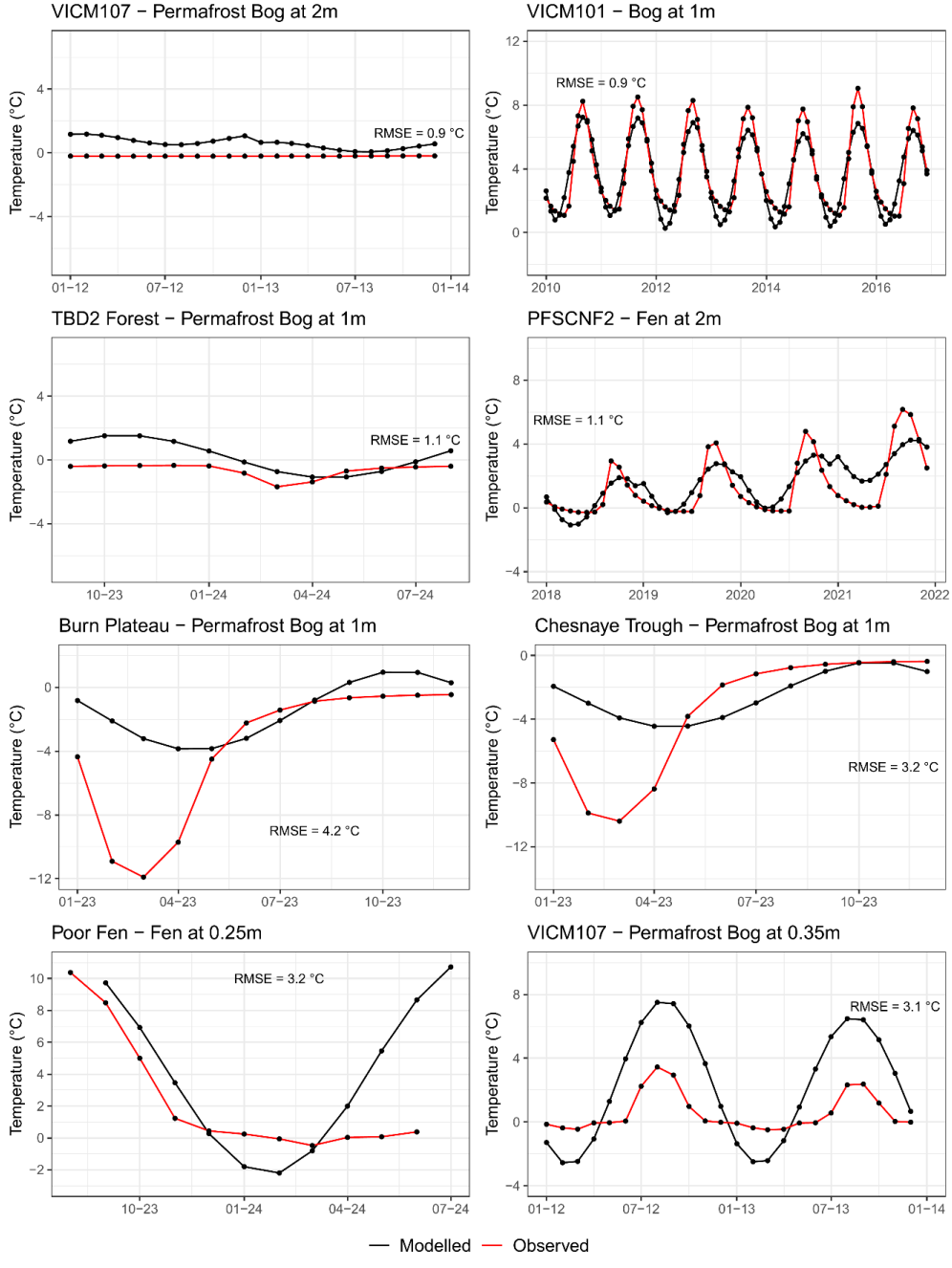


Figure 3. Time series plots for sites with the best (top four plots) and poorest (bottom four plots) model performance when compared to the observed temperature. Note the variability of the y axis scale between plots. Monthly root mean square error (RMSE) is given for each plot.

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Model performance varied among peatland classes. For most of the fen and bog sites, the modelled time series closely matched the observed. However, the model underestimated temperature (both the warmest and coldest) for most observations in bogs. Additionally, in permafrost bogs and permafrost fens, the model also underpredicted freezing season temperatures and overpredicted thawing season temperatures, especially at depths below the active layer.

3.2 Model Performance in a Southern Bog

In addition to the validation sites in the permafrost peatlands of Canada, the ground temperature model was also validated for SPRUCE bog sites in Northern Minnesota to assess model performance in a non-permafrost peatland (Hanson et al., 2015). The model performed well at these sites, producing an RMSE and r^2 similar to the northern validation bogs (Figure 4).

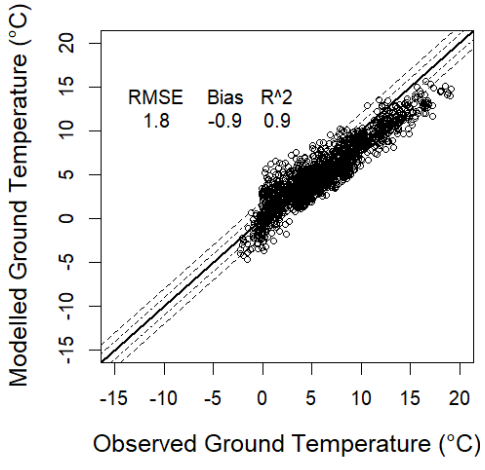


Figure 4. Scatter plot of monthly observed ground temperatures compared to modelled temperatures at the SPRUCE bog sites in Northern Minnesota. Solid black line shows the 1:1 ratio while the dashed lines indicate 1 and 2 ºC temperature error. Root mean square error (RMSE) and bias are given in °C.

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However, the model typically underpredicted temperature at the SPRUCE sites, leading to a larger cold bias than present in the northern validation bogs where temperatures were slightly overpredicted. This cold bias was also observed for the warmest bog temperature in the main (northern peatland) validation dataset.

3.3 Comparison to NEST Modelled Ground Temperature in the Hudson Bay Lowlands

For validation sites within the HBL, the ground temperature model performance was comparable to that of a more complex numerical model (NEST). CaMPground produced lower error on average (at both a monthly and annual scale) than the NEST model (Figure 5). While CaMPground overpredicted temperature, NEST underpredicted monthly temperatures by similar magnitude. Additionally, the r^2 for both models were similar. Based on depth, CaMPground produced a lower error than NEST for depths ≤ 0.5 m (RMSE of 2.2 °C compared to 2.5 °C) and for 1 m (2.0 °C compared to 2.8 °C). CaMPground produced lower errors than NEST for bogs (1.9 vs 3.1 °C), similar error for permafrost bogs (2.4 vs 2.3 °C), and higher errors for fens (1.6 vs 0.8 °C) and permafrost fens (1.6 vs 0.4 °C).

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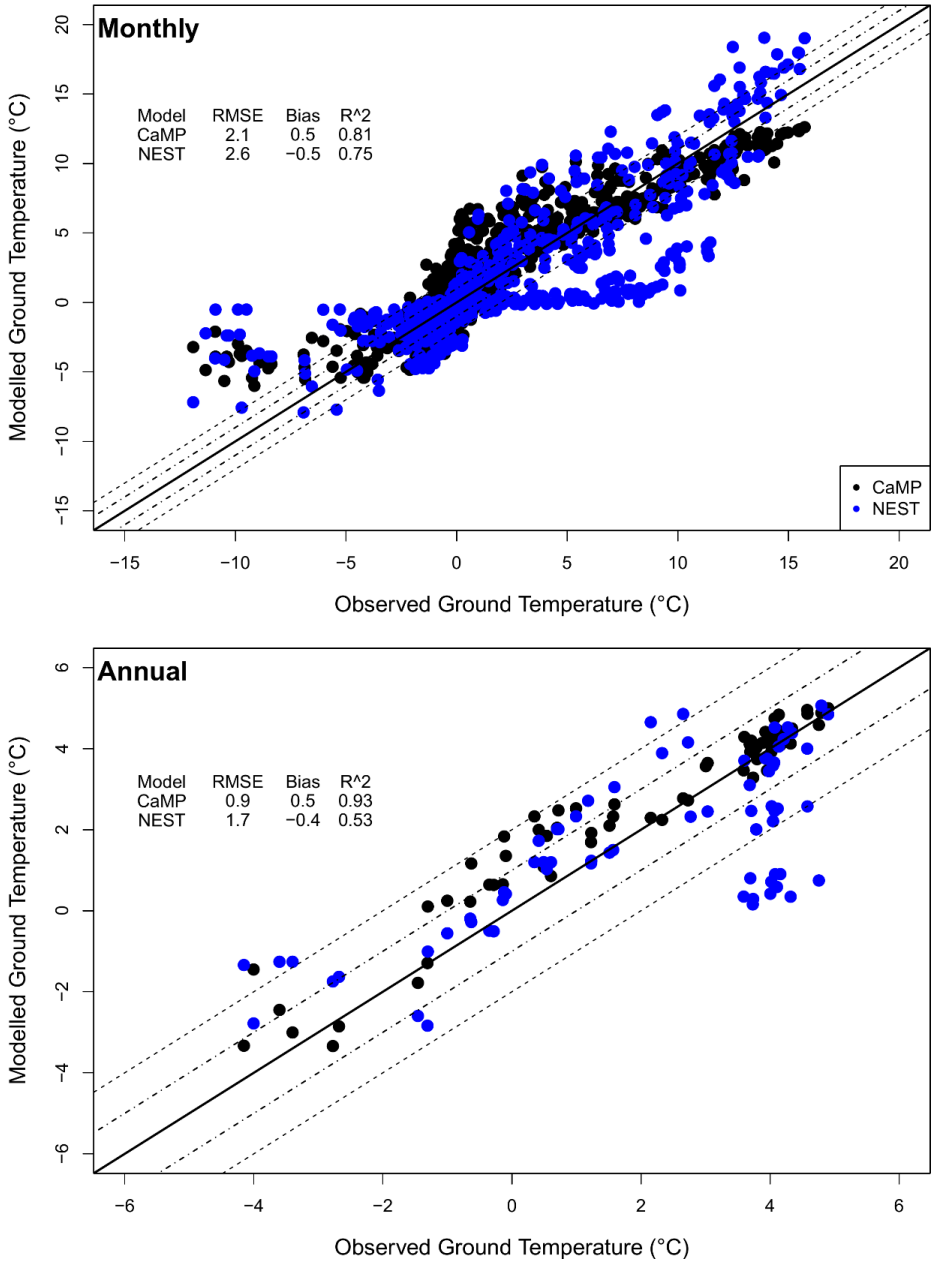


Figure 5. Scatter plots of the modelled ground temperature compared to the observed ground temperature at various depths for A) monthly and B) Annual time periods. Solid black line shows the 1:1 ratio while the dashed lines indicate 1 and 2 ºC temperature error. Root mean square error (RMSE) and bias are given in °C.

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CaMPground showed more consistent model performance across validation sites compared to NEST (Figure 6). CaMPground produced a lower error than NEST for a bog near Victor Mine, Ontario HBL at 1 m (Figure 6A). At the same site at 0.5m, both models had a similar error (Figure 6C). CaMPground also outperformed NEST at three permafrost bogs in the Northern Manitoba HBL at 1 m (6D, F and G). However, for two of the permafrost bogs, both models produced higher than average errors (Figure F and G). NEST produced lower errors than CaMPground for two permafrost bogs in the Northern Manitoba HBL at 1m (Figure 6B and E) and for a permafrost bog near Victor Mine at 0.5 m (Figure 6H). Although NEST outperformed CaMPground at sites with large seasonal asymmetry, CaMPground was more consistent, producing more moderate errors.

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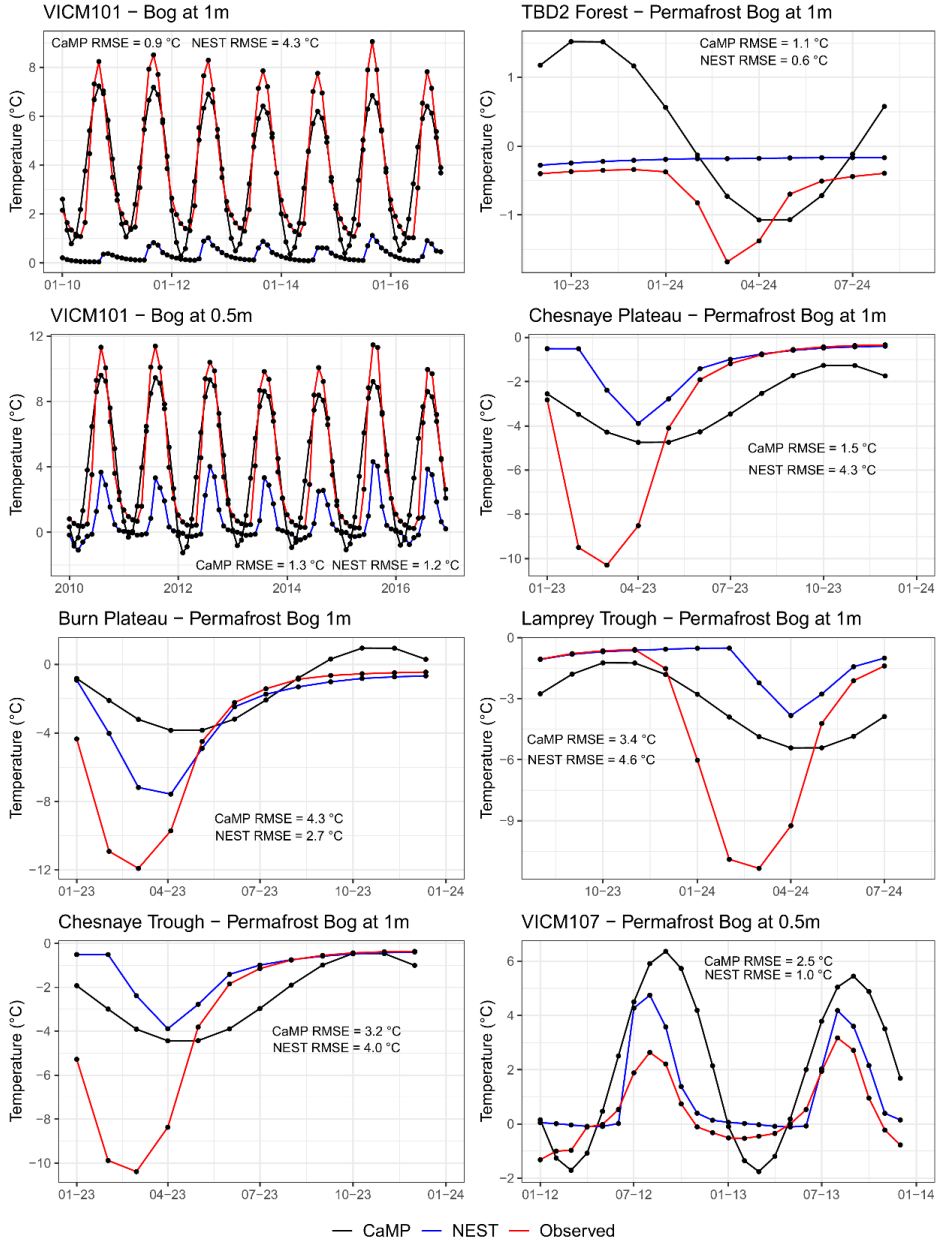


Figure 6. Time series plots for select sites comparing CaMPground and NEST predictions to observed temperature. Note the variability of the y axis scale between plots. Monthly root mean square error (RMSE) is given for each plot.

3.4 Model Performance for Simulating ALT

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The model overpredicted ALT for validation sites with permafrost (n = 13) across all peatland classes except at one permafrost bog. On average the modelled ground temperatures led to an overestimation of ALT by 48 cm across the two permafrost peatland classes, permafrost fens and permafrost bogs (Figure 7). ALT from the modelled ground temperatures, were slightly worse for permafrost bogs (RMSE of 83 cm) than for permafrost fens (RMSE of 66 cm) for which there were only two sites. CaMPground produced lower errors in ALT (3 - 40 cm) for the warmest permafrost bogs in the Ontario HBL (Figure 7J & M) and for permafrost bogs in the Manitoba HBL (Figure 7 C, F, G and I) with relatively cold ground surface temperatures (< 0 °C). For the Manitoba HBL permafrost bogs with relatively warm ground surface temperatures (> 0°C), the modelled ground temperature produced the larger errors in ALT (99 – 150 cm) (Figure 7 A, D, E, K, and L). There was also a larger difference in ALT predictions for permafrost fens when ± 1 standard deviation of k and d were used (Figure 7B & H). As a result, the RMSE for this peatland class could decrease to 34 cm for the minimum possible ALT or increase to 83 cm for the maximum possible ALT.

At all but two sites, NEST better predicted ALT (RMSE 28 cm) compared to CaMPground (RMSE 81 cm). However, at one permafrost fen (Figure 7B) and the warmest permafrost bog (Figure 7M), NEST predicted no ALT even when permafrost was confirmed to be present. ALT from the ESA produced similar ALT error (RMSE 71 cm) and ALT at the two warmest permafrost bogs (Figure 7 J and M) were substantially underestimated.

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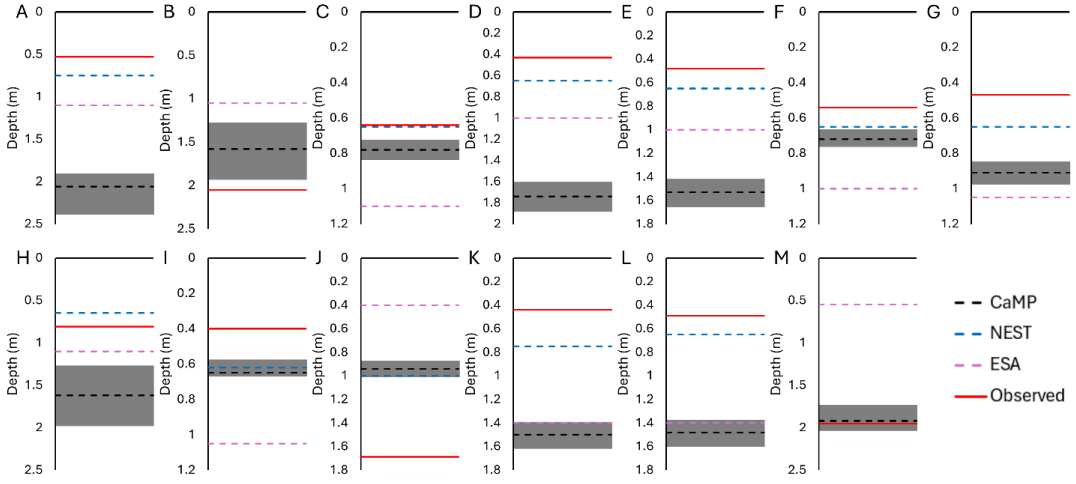


Figure 7. Active layer thickness estimated using CaMPground temperatures, from NEST, the European Space Agency, and estimated from observed temperatures at depth or probing for permafrost fens and permafrost bogs. Sites and peatland classes are A) Belcher Burn – Permafrost Bog, B) Belcher DL – Permafrost Fen, C) Belcher Plateau – Permafrost Bog, D) Bylot Forest – Permafrost Bog, E) Bylot Plateau – Permafrost Bog, F) Chesnaye Plateau – Permafrost Bog, G) Chesnaye Trough – Permafrost Bog, H) Lamprey Fen – Permafrost Fen, I) Lamprey Trough – Permafrost Bog, J) PFSCSP1 – Permafrost Bog, K) TBD2 Forest – Permafrost Bog, L) TBD2 Plateau – Permafrost Bog, and M) VICM107 – Permafrost Bog. The grey shading indicates an ALT calculated using ± 1 standard deviation for the model parameters.

4 Discussion

4.1 Variability in Model Performance

Although CaMPground produced relatively low errors across all peatland classes and sites, there was variability in performance based on peatland characteristics. The validation bogs showed limited freezing/thawing transitions (especially at deeper depths), which likely improved model performance at these sites. However, the validation bogs were the most southern in the dataset while the northernmost bogs in the dataset were used in model calibration. This may have contributed to the underprediction of the warmest temperatures as the amplitude decay rate is faster for locations with increased soil moisture freezing/thawing (Throop et al., 2012). However, the low error and high percentage of variance explained at the SPRUCE sites demonstrates that

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the calibrated bog parameters and model can be utilized accurately in locations outside of the HBL. It also highlights the similarity between bog thermal conditions across latitudes. However, as with fens, the increased seasonal differences in thermal conductivity may limit the applicability of the calibrated bog parameter values in more northern regions (Throop et al., 2012).

The model produced similar error for bogs and fens, which similarly had limited freeze/thaw transitions. However, fens showed larger seasonal asymmetry than bogs with a more pronounced zero-curtain (extended period of soil temperatures near zero due to latent heat exchange during freeze or thaw) during the freezing season, indicating longer freezing of soil moisture (Outcalt et al., 1990). At these sites, the model had increased error especially during freezing season months.

For the two peatland classes with permafrost (permafrost fens and permafrost bogs), the model performed well despite increased phase transitions. As the model does not account for latent heat effects, it often slightly overestimated the thawing season temperatures within permafrost. This was most apparent at northern HBL sites with top of permafrost temperatures close to 0 °C, as increased ice near the top of permafrost buffers thawing season temperatures (Shur et al., 2005). However, as the model accurately captures the temperature amplitude change with depth at these sites, the maximum temperature error was similar to the average RMSE (< 2.0 °C). Permafrost bog sites with the largest error resulted from a large overestimation of winter temperatures as the model did not account for reduced rate of amplitude change with depth due to increased thermal conductivity and apparent thermal diffusivity of frozen soil (Throop et al., 2012). While errors in the model likely stemmed from the model's simplicity – ignoring phase change and soil moisture – it still produced reasonable estimates of monthly temperatures at a

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variety of depths across the different peatland classes. Additionally, the underestimation of frozen temperatures in permafrost bogs will not likely impact the model's main objective – carbon stock modelling – as carbon exchange is halted for temperatures below 0 °C regardless of the temperature magnitude (Treat et al., 2021).

4.2 CaMPground Comparison to NEST

The difference in model performance between CaMPground and NEST was largely a product of the difference in model approach and complexity. As a numerical model, NEST was able to better incorporate freeze/thaw dynamics - including latent heat and soil moisture - leading to better temperature predictions at sites with substantial seasonal asymmetry and zero-curtain effect. This largely explains the lower error for NEST at fen, permafrost bog, and permafrost fen sites. However, CaMPground and NEST still had comparable RMSEs for these peatland classes (2.2 and 2.0 °C, respectively). This indicates that the indirect inclusion of soil moisture impacts on annual ground temperature and amplitude with depth (through the individual peatland class parameters) did not have a major impact on model performance.

CaMPground was also more consistent than NEST, producing similar RMSEs for all validation across all peatland classes and depths. This is potentially due to evenly weighting all depths during CaMPground calibration. In contrast, NEST focused calibration on permafrost temperatures, placing greater weight on temperatures deeper in the soil profile than temperatures near the ground surface. Additionally, NEST produced large errors for the one validation site in the bog class compared to the other peatland classes. This is perhaps due to an issue with the reanalysis input data at this site or the bog calibration but as there was only one site it may not be representative of NEST's performance in this class overall. The comparable error to NEST overall in the HBL demonstrates that despite its simplicity, CaMPground provides a good

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alternative for integration into a peatland permafrost peatland carbon models when complex numerical models cannot be used.

4.3 Model Performance at Simulating ALT

The error in ALT likely came from errors in the ground temperature predictions which were amplified by the binary nature of ALT predictions. Since the ground is either annually frozen below the AL and thawed above, even a small error in temperature can lead to large errors in ALT predictions. As a result, despite producing low RMSEs, CaMPground slightly over predicted temperatures in permafrost fens leading to thawed temperatures when the observed remained frozen. This led to large ALT overpredictions in these sites even though the predicted temperatures at 1m were close to the observed. As discussed previously, this likely came from the model's inability to account for the zero-curtain effect which was prevalent at the permafrost fens sampled. This also may explain why NEST was better able to predict ALT at one of these sites. However, NEST also failed to predict an ALT for the other validation permafrost fen. At this site the potential ALT was deeper than probing tools, however, the temperature recorded indicated frozen soil annually. Additionally, there were only a limited number of permafrost fens in calibration (n = 3) and validation (n = 2) which led to larger differences in the standard deviation of the calibrated parameters, so the inclusion of additional sites may improve model predictions of temperature and ALT. However, despite the limited number of observations, CaMPground still reasonably estimated ALT at these two sites and identified potential permafrost presence missed by NEST.

At individual permafrost bog sites, the CaMPground model larger temperature error was not indicative of large ALT error especially in the Ontario HBL and at relatively cold sites in Northern Manitoba. At the Chesnaye Trough permafrost bog, the temperature model error was

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Preprint. Discussion started: 16 November 2026
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one of the largest (RMSE of 3.2 °C) while the ALT error was one of the smallest (40 cm). This is likely because the larger temperature errors at this site came from an underestimation of permafrost temperatures. However, since the modelled temperatures were still predicted to be frozen, this error did not impact ALT estimations. Additionally, CaMPground ALT prediction errors were similar to those reported in other ALT modelling studies, especially for permafrost bogs in the Southern HBL and cold permafrost bogs in Northern Manitoba (Peng et al., 2018; Uxa et al., 2026). The large overestimations of ALT in permafrost bogs at the northern Manitoba portion of the HBL occurred at sites where ground surface temperatures were above 0 °C. Only one site used in calibration had a ground surface temperature above 0 °C and an ALT < 1m. Therefore, it is likely that the calibrated annual mean temperature decay (k) was not representative of these sites where the annual mean temperature decreases faster with depth. Additionally, these permafrost bogs only had one year of observation data. It is also possible that the ground surface conditions during this time were not representative of the typical thermal conditions, leading to better estimations using NEST, which utilizes historical conditions to establish permafrost presence, and ESA, which utilizes longer climate records. Finally, measured ALT at these sites were based on probing in early September; however, the measured temperature at 1 m often reaches its maximum later in the year (Rahman and Roy- Léveillée, *unpublished*). Although the ALT is shallower than 1 m, and therefore would reach its maximum temperature earlier, it is possible that the probing did not exactly correspond with maximum thaw, though this is not likely the main source of error.

Although CaMPground produced larger errors in ALT overall, compared to the NEST model and ESA estimations, it still has some advantages. Although NEST more accurately predicted ALT at most sites, it did not produce an ALT estimation for one permafrost fen and one

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Preprint. Discussion started: 16 November 2026
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permafrost bog where permafrost was confirmed to be present (through thermal observation). As a result, although CaMPground had larger errors across all sites, it still captured permafrost presence correctly at all sites. Finally, the sites where the CaMP model did not perform well (northern Manitoba HBL) are estimated to have lower peat thickness and carbon storage (and comprise a smaller area) compared to the sites where CaMP outperformed NEST and ESA (Li et al, 2025). Therefore, as CaMPground better estimated ALT at sites in the southern and interior HBL where organic layer thickness and carbon content are higher (and which spans a larger area of the HBL), CaMPground is still a viable option for carbon cycling modelling in this region.

4.4 Model Applications

The primary application for the ground temperature model will be for modelling carbon emissions and removals from permafrost peatlands within CaMP. As the ground temperature model can estimate monthly temperatures at multiple depths, the outputs can be used to estimate ALT annually. Using temperatures at two depths rather than ground physical properties to model ALT reduces the reliance on geophysical measurements, which can be sparse in remote permafrost regions like the HBL (Uxa et al., 2026). The ALT can then be used within CaMP to partition peat into unfrozen peat that participates in the carbon cycle, and frozen peat where carbon remains stable within the permafrost. The integration of the ground temperature model will also allow for annual changes in ALT (and thereby changes in the proportion of thawed to frozen peat) based on changing ground surface temperature. This allows different disturbance matrices for changing climate, wildfire, or permafrost bog collapse within permafrost environments, previously not considered, to be included in the CaMP model (Bona et al., 2020). Additionally, the integration of the ground temperature models enables CaMP to eventually become vertically resolved, tracking carbon movement between peat cohorts rather than acrotelm

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versus catotelm layers. Additionally, with further calibration of different peatland classes, the CaMPground framework could be used in upland forest ecosystems on mineral soils.

4.5 Model Limitations

Due to the model's simplicity and reliance on measured data, there are several limitations. First, although the model may indirectly account for soil moisture through the calibration of model parameters by peatland class, the model currently does not explicitly consider its impact on ground temperature or active layer thickness. This includes seasonal asymmetry due to latent heat exchange prolonging freeze up or thaw and the differential thermal conductivity between water and ice (Osterkamp & Romanovsky, 1997; Hinkel et al., 2001; Zhao et al., 2021). Additionally, years of increased soil moisture may also contribute to large interannual differences in ALT, when annual surface temperature conditions remain similar. However, there was no relationship between soil moisture (measured at a small number of sites and ERA5 and SMAP soil moisture products) and model error (Supplemental Material). Additionally, the model does not directly account for freezing/thawing processes (Woo, 2012). This likely results in the larger errors around 0 °C and the overestimation of summer temperatures within permafrost. Future CaMPground refinements will attempt to better integrate soil moisture dynamics and/or incorporate additional harmonics to better capture seasonal asymmetry (Woo et al., 2012; Wang et al., 2018).

CaMPground assumes constant soil thermal properties with depth (Holmes et al., 2008; Woo et al., 2012). While this assumption appears valid within the organic peat layer, this may not hold true if the model predictions extend into the mineral soil. If peat depth at the calibration sites is known, this could potentially be addressed through the calibration of parameters based on temperature observations within peat only and running the model until the substrate transition.

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However, this assumption does not appear to have an impact on model performance, as RMSEs for depths > 1 m (which may be beyond the peat depth) were similar to those at shallow depths (within peat).

Since the model parameters are empirically derived, the model performed better in locations and peatland classes with more calibration sites, such as permafrost bogs in the Ontario portion of the HBL, while performance was slightly poorer for permafrost fens in the Manitoba portion of the HBL where calibration sites were limited. As a result of the distribution of calibration sites concentrated in peatlands with discontinuous permafrost, the model gives accurate ground temperature predictions in permafrost and non permafrost peatlands south of the HBL. This is supported by the model performance in northern Minnesota. However, as model errors increased for continuous permafrost in the Manitoba portion of the HBL it is likely that model parameters should be recalibrated before use in permafrost peatlands north of the HBL. In addition to the distribution of sites since individual months and depths were treated as independent observations, sites with more sampling depths and longer records have a larger impact on the parameter value. Sites with the most observation depth and longest records were also located in discontinuous permafrost. However, despite these limitations, the model produced small errors for the different peatland classes across the HBL. Finally, the model was calibrated to 3 m, therefore using the model beyond this depth may result in increased uncertainty. However, as amplitude and annual average temperature decrease exponentially with depth, temperatures below 3 m are likely to be more consistent with depth than those closer to the ground surface.

5. Conclusion

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In permafrost peatlands, carbon modelling is complicated by the presence of thawed and frozen peat. A simple, sinusoidal ground temperature model was calibrated and validated for peatland classes in the HBL allowing permafrost dynamics to be integrated within peatland carbon models such as CaMP. Across all peatland classes, the model showed limited error (RMSE of 2.1 °C, monthly), particularly for both permafrost and non-permafrost fens. The model underestimated temperature amplitude and the warmest temperatures in bogs, potentially due to the inclusion of a bog underlain by permafrost in calibration. The calibrated bog parameters were also shown to be transferable to southern boreal bogs outside of the HBL. At the site level, the model was less accurate at sites and in peatland classes with significant zero curtain, which may explain the increased temperature errors in the permafrost bog class and ALT errors in permafrost fens. This indicates that the model could be improved by some incorporation of soil moisture or freeze/thaw dynamics, possibly by including second or third order harmonics into the model equation. This would allow for seasonal asymmetry in the sine wave. Additionally, the parameter values may be improved by including additional calibration sites from the northern HBL, as sites from this region were limited. However, despite its simplicity, the model showed similar errors (and better consistency between peatland classes) compared to a complex process-based model. Overall, this study showed that calibrated peatland parameters and a simple model can be used to estimate monthly ground temperatures at a variety of depths in the HBL. The model can be used as a framework to estimate ALT within CaMP to improve modelled carbon dynamics within permafrost peatlands.

Data Availability

Publicly available data used in this study can be found at the following

Labrador - https://doi.org/10.5885/45876XD-C1F55FCD3B95415D (Wang et al., 2024)

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Minnesota - https://mnspruce.ornl.gov/datasets/spruce-environmental-monitoring-data-2010-2016 (Hanson et al., 2015, http://dx.doi.org/10.3334/CDIAC/spruce.001)

Northwest Territories - https://doi.org/10.4095/pzyenpg5r0 (Holloway et al., 2026)

Yukon - https://doi.org/10.5281/zenodo.23403066 (Bonnaventure et al., 2026)

A portion of this data is not publicly available at this time as the data belongs to other institutions responsible for dissemination, but can be made available upon request to the corresponding author (madeleinegaribaldi9@gmail.com).

Code Availability

Sample ground temperature model script, ALT solver and calibration script can be found at https://doi.org/10.5281/zenodo.21495097 (Garibaldi et al., 2026).

Author Contributions

MCG – Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing (original draft preparation)

OH – Conceptualization, Formal analysis, Methodology, Writing (original draft preparation, review, and editing)

KLW – Conceptualization, Methodology, Funding acquisition, Supervision, Writing (review and editing)

HH – Conceptualization, Writing (review and editing)

EJSE – Conceptualization, Writing (review and editing)

KAB – Conceptualization, Writing (review and editing)

AC – Conceptualization, Funding acquisition, Writing (review and editing)

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YZ – Conceptualization, Methodology, Formal Analysis, Writing (review and editing)

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https://doi.org/10.5194/egusphere-2026-3394
Preprint. Discussion started: 16 November 2026
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Competing interests

The authors declare they have no competing interests.

Acknowledgements

We acknowledge sites used in this research are located on Akaitcho, Cree, Dena Kayeh, Gwich'in Nành, Ililiwaskiy Cree, Kaska, Métis, Michif Piyii, Nitassinan, Nunatsiavut, Na-cho Nyak Dun, Tr'ondëk Hwëch'in, Shita Got'ine, Tłı̨chǫ Ndè, Vunlut Gwich'in settlement regions and traditional territories. Funding for this paper was provided by the Natural Science and Engineering Research Council, the Northern Scientific Training Program, Polar Knowledge Canada, Natural Resources Canada, Parks Canada, Government of the Northwest Territories, W. Garfield Weston Foundation, University of Lethbridge, University of Alberta, University of Ottawa, Université Laval, Queen's University and Government of Ontario. We would also like to thank the numerous colleagues who have contributed to data collection over the years. Finally, we would like to thank G. Seutin for review before submission.

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