Evaluating local drivers of ground surface temperature variability in coastal Labrador

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Abstract

Disentangling the contrasting influences of local ecosystem properties on soil temperatures is critical to understanding drivers of spatial variability in ground thermal conditions and permafrost distribution. In this study, we investigate the influence of vegetation, snow, and soil conditions on ground surface temperatures at two subarctic research basins in coastal Labrador. Eighteen ground surface temperature loggers were deployed at each basin using a stratified random deployment protocol based on land cover and snow thickness strata obtained from summer and winter uncrewed aerial vehicle surveys. Site-specific field information was also collected at each logger location in both summer and winter to contextualize ground surface temperature variability. At the southern field site (Pinware River Hills), derived microclimate indices had statistically significant associations with ground temperatures, whereas at the northern site (Nain Bay Hills), ecosystem properties including snow thickness, were important predictors of temperature variability. Ensemble model simulations of permafrost probability indicate that only 10% of loggers had more than 50% probability of having permafrost, but all of these loggers were found at Nain Bay Hills in low-snow tundra and wetland ecotypes. This research will inform regional permafrost distribution modelling and our understanding of the microclimate drivers or ground temperature variability in northern regions.

1 Introduction

Permafrost is an important component of the terrestrial cryosphere, storing carbon (Schuur et al. 2015), supporting habitat for keystone species (Joly et al. 2021), and sustaining traditional activities for Indigenous Peoples (Anderson et al. 2018). Permafrost thaw due to ongoing changes in climate and land use (Biskaborn et al. 2019; Suter et al. 2019) increases the potential for ecosystem modifications (Jin et al. 2021; Olefeldt et al. 2021). Most studies predict that permafrost in the discontinuous zone will be the first to thaw because it is usually in disequilibrium with current climate (Biskaborn et al. 2019; Holloway and Lewkowicz 2019; Hrbáček et al. 2019). However, regional permafrost changes are expected to be heterogenous because variability in snow, vegetation, and soil characteristics alter the susceptibility of landscapes to permafrost thaw (Grünberg et al. 2020; Myers-Smith and Hik 2013; Zhang et al. 2021). As these factors can vary over sub-meter scales, it is challenging to evaluate permafrost characteristics at high spatial resolution via remote sensing, especially with large gaps in permafrost observation networks (Philipp et al. 2021; Smith et al. 2005).

Previous research has shown that permafrost distribution in upland areas can be particularly heterogeneous (von Oppen et al. 2022; Zhang et al. 2021). Microclimatic conditions such as vegetation height, snow cover, and soil characteristics all influence the local thermal exchanges, resulting in highly variable ground thermal regimes (Mott et al. 2018; Myers-Smith and Hik 2018; Strum et al. 2001). This variability can be amplified in coastal mountainous areas (Davesne et al. 2017) where ground surface temperatures often vary by 2–4 °C across short distances (< 1 m) due to differing snow thicknesses; thicker snow insulates the ground surface from seasonal and daily air temperature fluctuations, resulting in warmer ground temperatures (Gisnås et al. 2016).

Recent technological advances have facilitated extensive data logger deployments across large study areas, opening new opportunities to quantify the drivers of local scale variability in ground temperatures (Garibaldi et al. 2021; Șerban et al. 2023). However, many of these studies have focused on field sites with low regional snowfall totals. As such, there are fewer observed ground surface temperatures (GST) in coastal discontinuous permafrost environments where high snow conditions can enhance variability (Bense et al. 2016; Lembrechts et al. 2020).

In this study, we investigate local-scale variability in GST at two low-relief coastal mountain research basins (Pinware River Hills and Nain Bay Hills) located at the extreme ends of the discontinuous permafrost zone in coastal Labrador. GST variability was analyzed together with in situ vegetation, snow, and soil characteristics to elucidate the effect of microclimate conditions on the ground thermal regime. These results will contribute to a better understanding of local microclimate impacts on ground temperatures.

2 Methodology

Data were collected from two hilltop plateau research basins (Pinware River Hills [PRH] and Nain Bay Hills [NBH]) located in low-relief coastal mountains in Labrador, Canada (Figure 1). Both sites were chosen following consultation with regional partners and aim to maximize variability in snow redistribution (0–5 m), ecotype (forest-tundra

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transition), and surficial deposits (till, bedrock, peat; Tutton et al. 2021). PRH (51.7°N, 56.6°W) is at the southern limit of the isolated patches of permafrost zone on lands claimed by the NunatuKavut Community Council. NBH (56.6°N, 62.0°W) is in the Labrador Inuit Settlement Area (Nunatsiavut) and is at the northern limit of the sporadic discontinuous permafrost (Way and Lewkowicz 2018). Eighteen locations (1 by 1 m) at both PRH and NBH were selected for logger deployment covering three ecotypes (upright vegetation, wetland, or tundra) and six snow thickness ranges.

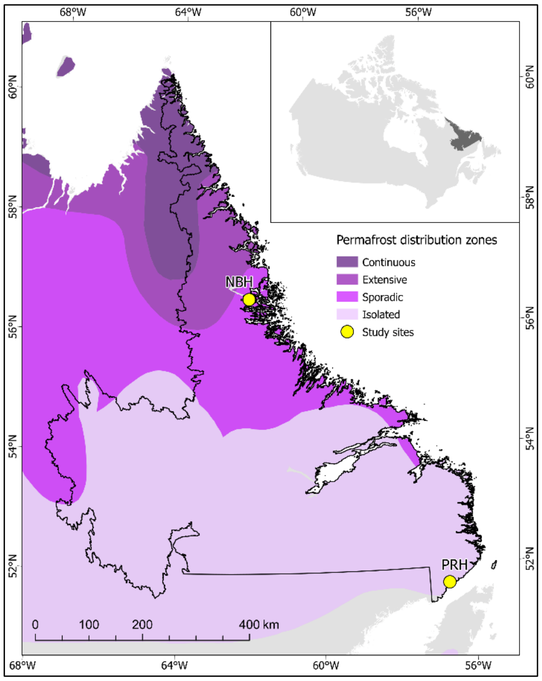

Figure 1. Location of Nain Bay Hills (NBH) and Pinware River Hills (PRH) research basins superimposed on permafrost distribution zones (Heginbottom et al. 1995).

2.1 Uncrewed Aerial Vehicles (UAV) surveys

UAV surveys were used to evaluate site characteristics (Cryderman et al. 2014; Harder et al. 2016) and to inform site selection and sampling strategies. Summer UAV surveys were collected in 2019 (PRH) and 2021 (NBH), while winter UAV surveys were collected in 2020 (PRH and NBH). Image acquisitions (450 m by 450 m double grids) used a DJI Mavic 2 Pro equipped with a 4K Hasselblad camera flown at 90 m above ground level (ground sampling distance: ~2.3 cm). Summer UAV image acquisitions used High Latitude Drone Ecology Network (HiLDEN) data collection protocols (Assmann et al. 2017), while winter UAV image acquisitions followed Walker et al. (2020). Ground control points (n = 10) were collected for each UAV flight using an Eos Arrow Gold GNSS with real-time Atlas corrections differential GPS (DGPS; VRMS < ± 8 cm). Point clouds and orthomosaics were generated using Pix4D, and digital surface models (DSM) and digital terrain models (DTM) were generated using Esri ArcMap 10.7.

UAV orthomosaics were classified according to major land cover strata (tundra, wetland, upright vegetation, bare rock, and water) with a support vector machine object-based supervised classification in ArcMap 10.7. A 1 m resolution late-winter snow depth map was obtained for each site by differencing winter DSMs from summer DTMs with small edits to remove protruding branches (Walker et al. 2020). UAV-derived snow depths for both PRH and NBH were reclassified into six strata (0–0.3 m, 0.3–0.6 m, 0.6–0.9 m, 0.9–1.2 m, 1.2–1.8 m, > 1.8 m) and were combined with three ecotypes (tundra, wetland, upright vegetation) to obtain 18 unique classes.

2.2 GST logger deployment

Thirty-six GST loggers were deployed in summer 2020 (PRH, n = 18) and summer 2021 (NBH, n = 18) at random locations within the UAV-informed 18 unique strata for each site (Figure 2). Navigation to the generated positions (± 40 cm) used a DGPS (Eos Arrow Gold RTK GNSS Receiver). At each point, HOBO MX2203 temperature data loggers (± 0.25 °C) collecting bi-hourly temperature readings were buried 5 cm beneath the ground surface, and locations were marked with metal stakes and flagging tape (Figure 3). Loggers were re-downloaded (35/36; 97% success rate) in summer 2022 enabling a full year of data collection (September 2021 – August 2022) to be analyzed.

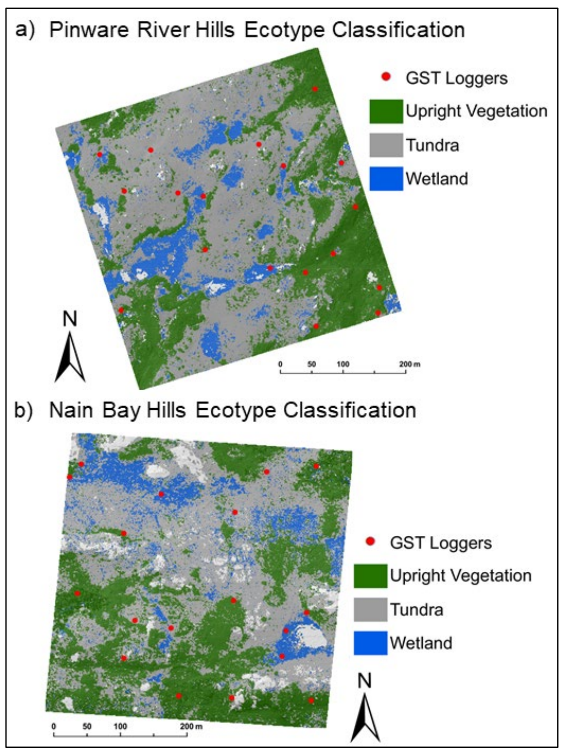

Figure 2. Ground surface temperature logger locations in a) Pinware River Hills and b) Nain Bay Hills field sites by ecotype. Water and bare rock are shown in white.

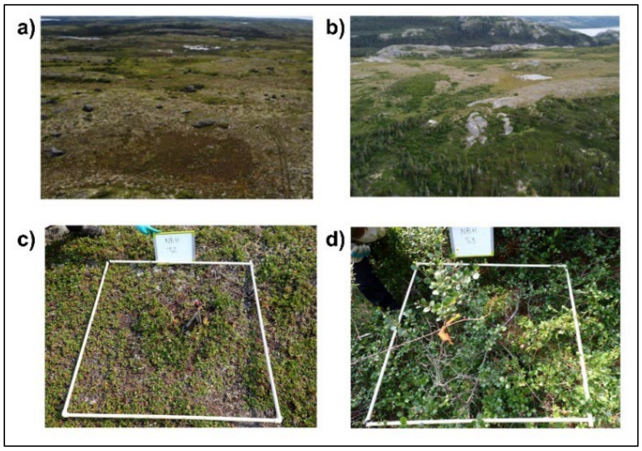

Figure 3. Oblique UAV view of field sites for a) Pinware River Hills (PRH) and b) Nain Bay Hills (NBH) with a c) tundra and d) upright vegetation logger deployment site from NBH.

2.3 Site characterization

At each logger deployment site, vegetation and soil characteristics were collected in summer 2021 and summer 2022. Vegetation plots (1 m by 1 m quadrat) and visual estimates were used to determine percent cover for key functional plant groups (lichen, moss, short shrub, tall shrub, tree, and herbaceous plants) and dominant plot species. Soil conditions were described using small (30 by 30 cm) soil pits dug to the base of the organic layer which enabled the description and thickness of the organic layer and mineral soil texture. Three instantaneous soil moisture measurements were also taken at a 20 cm depth using an Extech MO750 soil moisture meter (± 0.1%).

Late-winter snowpack conditions in mid-March 2022 at PRH and NBH were characterized at each logger position by relocating each logger (± 30 cm of true position) using a DGPS (Broxton et al. 2019; Dong 2018). Snow water equivalents (SWE) and snow densities were calculated for each point using mass measurements of snow cores (Geo Scientific Ltd.) taken within 30 cm of logger location.

Microclimate indices were calculated for each of the 35 logger locations in combinations with the air temperature data recorded at each station within 400 m of each logger (Table 1). The freezing n-factor (nf) is a unitless ratio between the freezing degree days of the soil (FDD_s) and the freezing degree days of the air (FDD_a), while the thawing n-factor (nt) is the ratio between the thawing degree days of the soil (TDD_s) and the thawing degree days of the air (TDD_a; Burn et al. 2004; Klene et al. 2001; Liu et al. 2021). Nival offset (NVO) and thawing surface offset (TSO) were calculated using the difference between the FDD_a and FDD_s or TDD_a and TDD_s, respectively, divided by the number of days (i.e., 365 days; Way and Lewkowicz 2018). These microclimate indices summarize air-surface temperature differences and vary depending on snow and vegetation characteristics. Higher (lower) nf (NVO) values suggest thinner snow cover and lower (higher) nt (TSO) values suggest taller and/or denser vegetation cover (Hasler et al. 2015; Throop et al. 2012). Surface offset (SO) was also calculated using the difference between the mean annual ground surface temperature (MAGST) and mean annual air temperature (MAAT) to summarize the net effect of nival and thawing offsets over the year (Smith and Riseborough 2002). A correlogram between collected and derived variables was used to examine the general statistical associations between variables and MAGST.

Table 1. Derived microclimate indices.

Indices	Equation	Units
Freezing n-factor (nf)	FDDs÷FDDa	Unitless
Thawing n-factor (nt)	TDDs÷TDDa	Unitless
Nival Offset (NVO)	(FDDa-FDDs)÷365	°C
Thawing Surface Offset (TSO)	(TDDs-TDDa)÷365	°C
Surface Offset (SO)	GST-MAAT	°C
Thermal Offset (TO)	MAGT-GST	°C

2.4 Analysis of permafrost probability

The temperature at the top of permafrost (TTOP) model is a process-based equilibrium permafrost model (Smith and Riseborough 2002) that has been previously used with GST loggers to characterize permafrost distribution (Garibaldi et al. 2021). The mean annual ground temperature at the top of permafrost or the base of seasonal freezing (e.g., MAGT at TTOP) for a given logger location can be estimated by adding a thermal offset (TO; Burn et al. 2004) to MAGST following Davis et al. (2021):

$$TTOP = TO + MAGST \quad [1]$$

The MAGT at the top of permafrost was estimated for each logger location using the measured MAGST and an ensemble of TO estimates for each logger, where the ensemble of TOs were generated using observed TOs from field monitoring locations at PRH (n = 3) and NBH (n = 3) established by Tutton et al. (2021). Following Davis et al. (2021), we generated 1,000 simulated TOs (R(4.1.1)) using the mean (PRH: -0.48 °C; NBH: -0.55 °C) and standard deviation (PRH: 0.25 °C; NBH: 0.48 °C) of TOs measured at the research basins assuming a normal distribution. The ensemble was then applied (Eq.1) to the MAGST of each logger (n = 35) to generate estimates (n = 1,000) of MAGT at TTOP for each logger.

3 Results

3.1 Variability in ground temperatures

MAGSTs averaged 3 °C (range: 2.4–3.9 °C) at PRH and 1.8 °C (range: -0.9 to +3.7 °C) at NBH. Basin-wide differences in MAGST between PRH and NBH were statistically significant (t-test, $p < 0.05$), but when stratified by ecotype, only tundra ($p < 0.05$) and upright vegetation ($p < 0.05$) showed significant differences between the basins. Partitioned by field site, ecotype showed no statistically significant differences at PRH, while at NBH, only differences between tundra and upright vegetation ecotypes were near statistical significance ($p < 0.10$). Greater MAGST was observed at PRH for all ecotypes compared to NBH (Figure 4). At NBH, variability was higher for tundra (sd: 1.5 °C) and wetland (sd: 1.5 °C) ecotypes than upright vegetation (sd: 0.6 °C), whereas at PRH, variability was greatest in the upright vegetation class (sd: 0.4 °C) and lowest in tundra (sd: 0.3 °C).

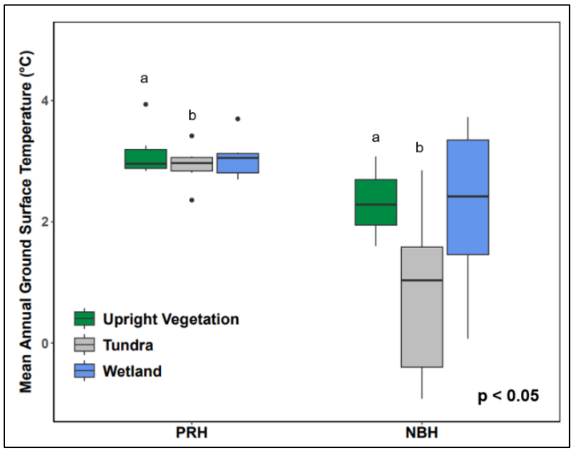

Figure 4. Mean annual ground surface temperatures (MAGST) recorded by data loggers (n = 35) stratified by research basin (Pinware Rive Hills [PRH] and Nain Bay Hills [NBH]) and ecotype. Statistical differences ($p < 0.05$) between tundra and shrub ecotypes between sites.

Derived freezing metrics (nf and NVO) showed contrasting results between PRH and NBH. The nf and NVO were significantly lower at PRH (mean: nf = 0.13, NVO = 3.3 °C) compared to NBH (mean: nf = 0.25, NVO = 4.5 °C). Stratified by ecotype, nf was the lowest for the upright vegetation ecotypes (PRH: 0.09; NBH: 0.11), indicating limited ground freezing in upright vegetation areas in winter. Similarly, at both sites, mean NVO was the highest at the upright vegetation ecotype (PRH: 3.4 °C; NBH: 5.3 °C) and lowest for tundra (PRH: 3.1 °C; NBH: 3.4 °C).

Air-surface temperature differences in the warm season (nt and TSO) showed smaller differences between the field sites. Nt was slightly lower at NBH (mean: nt = 0.98) compared to PRH (mean: nt = 1.02), whereas TSO was significantly lower at PRH (mean: -1.0 °C) compared to NBH (mean: -0.5 °C; t-test: $p < 0.05$). These data suggest that air-surface temperature differences in the warm season impact PRH more than NBH, but the magnitude of these effects is generally small (usually less than 1 °C). For both field sites, mean TSO was highest at the wetland ecotype (PRH: -0.4 °C; NBH: -0.7 °C) and lowest at the upright vegetation ecotype (PRH: -0.6 °C; NBH: -1.4 °C), indicative of shading and moisture effects on microclimate.

3.2 Correlations between local site properties

Correlograms were used to evaluate and visualize the statistical associations of MAGST and local site properties (Figure 5). Pooling PRH and NBH together, statistically significant Pearson correlations ($p < 0.05$) were observed between MAGST and most variables, except for number of snow days, nt and NVO. The highest correlation was observed between MAGST and nf (r = -0.89). For PRH, MAGST was significantly correlated with nf, SO, NVO, and TSO, with the strongest correlation found with SO (r = 0.99) and nf (r = -0.70). At NBH, MAGST had statistically significant correlations with SWE, snow depth, snow density, nf, SO, and NVO, with the strongest associations with SO (r = 0.99) and nf (r = -0.93).

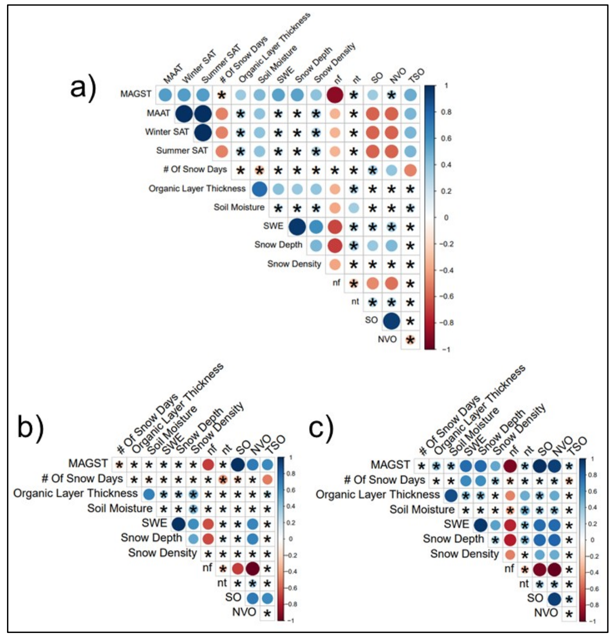

Figure 5. Correlogram of the variables obtained at each logger location for a) both field sites (n = 35), b) PRH (n = 18), and c) NBH (n = 17). Areas without an asterisk show significant correlations ($p < 0.05$), circle size indicates the magnitude of the correlation, and the colour indicates the direction. Note: winter and summer SAT are seasonal averages of air temperature at the two basins.

The derived indices show uneven positive and negative correlations among the pooled sites. nf was significantly negatively correlated with every variable except the number of snow days whereas NVO was both negatively and positively correlated with measured and derived variables. Divided by basins, freezing indices were more correlated at NBH compared to PRH, showing that snow is more important for understanding ground thermal variability at this more northern site.

The pooled data showed that nt was not significantly associated to any factors whereas TSO showed a positive correlation with air temperature (r = 0.46) and a negative correlation with the number of snow days (r = -0.49). Thawing indices showed no significant correlation at NBH, while at PRH correlations were only present for MAGST (r = 0.64) and the number of snow days (r = -0.51). Together these data suggest a lack of consistency in the statistical associations between derived microclimate indices, local site characteristics, and MAGSTs, highlighting the need for additional analyses using other statistical techniques, like structural equation modelling.

3.3 Permafrost distribution

The ensemble-based permafrost simulations showed that there was only a 9.7% probability of permafrost averaged across all 35 loggers at PRH and NBH. Only eight loggers had simulation results indicating permafrost was plausible (> 0% probability), with just three considered likely (> 50% probability). All possible and likely permafrost sites were located at NBH (Figure 6). This was interpreted to be partly because of lower overall MAGSTs at NBH but also because of greater MAGST variability and a larger range of thermal offsets used at NBH compared to PRH (PRH: -1.2 °C to 0.4 °C; NBH: -2.1 °C to 0.9 °C). Two of the three loggers where permafrost was considered likely were in tundra ecotypes and the other was in a wetland ecotype. All three likely permafrost sites had shallower snow depths (≤ 45 cm) compared to non-permafrost logger sites (> 45 cm).

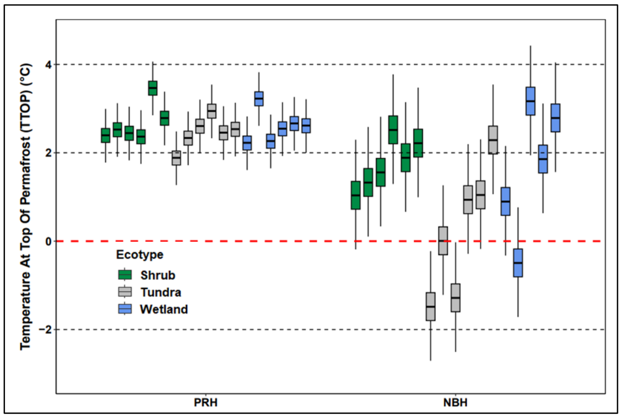

Figure 6. Ensembles of simulated temperatures at top of permafrost (TTOP) (n = 1,000) for the 35 GST loggers simulated using thermal offsets and observed MAGSTs for Pinware River Hills (PRH) and Nain Bay Hills (NBH).

4 Discussion

4.1 Variability in ground temperatures

GSTs in coastal Labrador varied considerably between the two research basins and between ecotypes. Greater within-ecotype variability was observed at the northern field site (NBH) than at the southern field site (PRH). These results are similar to those reported by Tyystjärvi et al. (2023) who found that MAGST variability increased with latitude at field sites in Finland, although Odland et al. (2017) did not find a similar latitudinal association in the Norwegian mountains. In the latter study, the authors reported greater MAGST variability than reported here but this is likely due to the comparatively smaller range in mean annual air temperature for the two basins investigated in the current study. The absence of permafrost at PRH and the low probability of permafrost at NBH may be an important contributor to muted MAGST variability, as deeper ground temperatures can exert a significant influence on near-surface soil temperatures (Riseborough et al. 2008; Smith and Riseborough 2002).

Our study did not find statistically significant differences in MAGST between ecotypes at either PRH or NBH, although the p-values at the latter basin approached significance ($p < 0.10$). This result may be explained by the logger deployment approach which ensured similar strata for snow depth between the ecotypes. Larger sample sizes, particularly at NBH, could have increased our ability to statistically detect smaller effect sizes. Aalto et al. (2018) concluded that local scale vegetation influences on ground temperatures in Finland were non-uniform with vegetation-snow interactions, leading to warmer ground temperatures due to air-surface decoupling. Conversely, Evans et al. (2022) found that at their study sites on Baffin Island, the associations between vegetation type and variability in GSTs was indirect. Instead, their findings emphasized that snow duration and microtopography exerted a more significant influence on the ground thermal regime compared to vegetation characteristics. These contrasting findings highlight the importance of study design and stratified logger deployment to ensure that GST data include a wide range of ecotypes and snow covers.

4.2 Drivers of ground temperature variability

This analysis demonstrated statistically significant associations between multiple measured and derived variables, though the strength of these associations varied when stratified by study sites. Specifically, MAGST at NBH was most correlated with snow indices (SWE, nf, NVO), whereas MAGST at PRH was significantly correlated with derived indices (SO, NVO, TSO). Stronger overall associations found at NBH compared to PRH highlight the role of regional climate differences in altering linkages between ground temperatures and local ecosystem properties, as shown previously in model scenarios by Way and Lapalme (2021). Strong correlations between winter season indices (nf, NVO) and MAGST at NBH agree with a large-scale analysis of 106 subarctic and Arctic sites by Kropp et al. (2020) who found that MAGSTs are more sensitive to variability in winter season conditions. Like Way and Lewkowicz (2018), we observed that air-surface temperature differences in the summer were correlated with the number of snow days which is suggestive of a link between late-lying snow and delayed soil temperature warming (Grünberg et al. 2020). While these associations can provide important context to the ground thermal regime, effect size cannot be determined using correlations alone and differences between basins underscores the necessity of synthesizing data from multiple sites for drawing broader conclusions.

4.3 Permafrost probability

Permafrost is likely present for low snow tundra ecotypes across NBH. This result highlights the importance of considering the effects of snow and vegetation in regional permafrost assessment. Little to no snow accumulation allows colder temperatures to be reached at the surface for longer preserving permafrost at deeper depths (Biskaborn et al. 2019). The wetland ecotype site at NBH where a high permafrost probability was estimated is near a small palsa where the permafrost is insulated by a thick layer of peat. Research by Wang et al. (2023) concluded that peatland permafrost was significantly underestimated for the

Labrador coast and that contemporary models may not be adequately representing permafrost distribution in coastal wetlands. Our results show that even at upland sites peatland permafrost can be found in localized environments with thick peat deposits and minimal snow cover.

4.4 Limitations

Although this study explores many factors influencing local-scale variability in the ground thermal regime, caution is needed to avoid over-extrapolating the results given some key limitations. The single largest limitation is the short period of analysis (one hydrological year) which could lead to differences in basin-wide MAGST compared to longer-term averages (Hargrove and Pickering 1992; Nakagawa and Cuthill 2007). This analysis intended to use two hydrological years, but owing to COVID-19 travel restrictions, NBH was not able to be visited for logger deployment until 2021. For PRH, logger deployment occurred in 2020, but we restricted our analysis to 2021–2022 to ensure comparability with NBH. The short duration of records could also impact the correlation analysis because interannual variability may affect associations between variables but overall zones of high (low) snow accumulation tended to be similar across years and changes in vegetation are generally subtle over short time periods (Myer-Smith and Hik 2013). Future work could build on these results using additional years of data from these study sites and more advanced statistical techniques to better represent spatio-temporal drivers of variability.

5 Conclusions

This study provides new insights into variability of near-surface ground temperatures in northern coastal environments using observations spanning two ends of the discontinuous permafrost zone in subarctic Labrador, northeast Canada. Using a stratified random logger deployment scheme, we were able to explore local scale variations in MAGST across a range of ecotypes and snow conditions. Our results showed that soil temperature variability was greatest at our northern site (NBH) where soil temperatures were lower. We also found that statistical associations with local site properties were also greater at NBH than PRH. These results suggests that macroclimate conditions, like regional permafrost distribution, can dictate or mediate the associations between local ecosystem properties and ground temperatures in subarctic regions. An analysis of permafrost distribution using ensembles of model simulations showed that permafrost is absent from PRH but can be found in certain environments at NBH including low snow tundra and wetland ecotypes.

Ongoing and future changes in temperature, precipitation, and land cover, coupled with expanded development in the Canadian north will necessitate an improved understanding of changes to local microclimate in highly heterogeneous environments like those presented in this study. Our study also highlights the utility of UAVs for supporting stratified sampling designs which can improve the extrapolatability of analyses of the ground thermal regime. This study will contribute to the development and evaluation of next-generation permafrost distribution models in Labrador, and will support the development of climate adaptation strategies for permafrost thaw and ecosystem shifts.

6 References

Aalto, J., Scherrer, D., Lenoir, J., Guisan, A., and Luoto, M. 2018. 'Biogeophysical controls on soil-atmosphere thermal differences: Implications on warming Arctic ecosystems', *Environmental Research Letters* 13, 074003. Available at: https://doi.org/10.1088/1748-9326/aac83e.

Anderson, D., Ford, J.D., and Way, R.G. 2018. 'The Impacts of Climate and Social Changes on Cloudberry (Bakeapple) Picking: A Case Study from Southeastern Labrador., *Human Ecology: An Interdisciplinary Journal* 46(6), pp. 849–863. Available at: https://doi.org/10.1007/s10745-018-0038-3.

Assmann, J., Kerby, J., and Myers-Smith, I. 2017. 'HiLDEN: Spectral Calibration and Guidance', *Drone Ecology Network*. Available at: https://arcticdrones.org/2017/05/12/high-latitude-drone-ecology-network-multispectral-flight-protocol-and-guidance-document/.

Bense, V.F., Read, T., and Verhoef, A. 2016. 'Using distributed temperature sensing to monitor field scale dynamics of ground surface temperature and related substrate heat flux', *Agricultural and Forest Meteorology* 220, pp. 207–215. Available at: https://doi.org/10.1016/j.agrformet.2016.01.138.

Biskaborn, B.K., Smith, S.L., Noetzli, J., Matthes, H., Vieira, G., et al. 2019. 'Permafrost is warming at a global scale', *Nature Communications* 10, 264. Available at: https://doi.org/10.1038/s41467-018-08240-4.

Broxton, P.D., van Leeuwen, W.J.D., and Biederman, J.A. 2019. 'Improving Snow Water Equivalent Maps With Machine Learning of Snow Survey and Lidar Measurements', *Water Resources Research* 55(5), pp. 3739–3757. Available at: https://doi.org/10.1029/2018WR024146.

Burn, C.R. 2004. 'The Thermal Regime of Cryosols', in J. M. Kimble (ed.), *Cryosols: Permafrost-Affected Soils*. Berlin, Germany: Springer, Berlin, Heidelberg. Available at: https://doi.org/10.1007/978-3-662-06429-0_19.

Cryderman, C., Mah, S.B., and Shufletoski, A. 2014. 'Evaluation of UAV Photogrammetric Accuracy for Mapping and Earthworks Computations', *GEOMATICA* 68(4), pp. 309–317. Available at: https://doi.org/10.5623/cig2014-405.

Davesne, G., Fortier, D., Domine, F., and Gray, J.T. 2017. 'Wind-driven snow conditions control the occurrence of contemporary marginal mountain permafrost in the Chic-Choc Mountains, south-eastern Canada: A case study from Mont Jacques-Cartier', *The Cryosphere* 11(3), pp. 1351–1370. Available at: https://doi.org/10.5194/tc-11-1351-2017.

Davis, E., Trant, A., Hermanutz, L., Way, R.G., Lewkowicz, A.G., Siegwart Collier, L., Cuerrier, A. and Whitaker, D. 2021. ‘Plant–Environment Interactions in the Low Arctic Torngat Mountains of Labrador’, *Ecosystems* 24, pp. 1038–1058. Available at: https://doi.org/10.1007/s10021-020-00577-6.

Dong, C. 2018. ‘Remote sensing, hydrological modeling and in situ observations in snow cover research: A review’, *Journal of Hydrology* 561, pp. 573–583. Available at: https://doi.org/10.1016/j.jhydrol.2018.04.027.

Evans, S.G., Raberg, J.H., Crump, S.E., Raynolds, M.K., Sugg, M.M., Brodie, A.R., and Miller, G.H. 2022. ‘Control of Short-Stature Vegetation Type on Shallow Ground Temperatures in Permafrost Across the Eastern Canadian Arctic’, *Journal of Geophysical Research: Biogeosciences* 127(7), e2022JG006941. Available at: https://doi.org/10.1029/2022JG006941.

Garibaldi, M.C., Bonnaventure, P.P., and Lamoureux, S.F. 2021. ‘Utilizing the TTOP model to understand spatial permafrost temperature variability in a High Arctic landscape, Cape Bounty, Nunavut, Canada’, *Permafrost and Periglacial Processes* 32(1), pp. 19–34. Available at: https://doi.org/10.1002/ppp.2086.

Gisnås, K., Westermann, S., Schuler, T.V., Melvold, K., and Etzelmüller, B. 2016. ‘Small-scale variation of snow in a regional permafrost model’, *The Cryosphere* 10(3), pp. 1201–1215. Available at: https://doi.org/10.5194/tc-10-1201-2016.

Grünberg, I., Wilcox, E.J., Zwieback, S., Marsh, P., and Boike, J. 2020. ‘Linking tundra vegetation, snow, soil temperature, and permafrost’, *Biogeosciences* 17(16), pp. 4261–4279. Available at: https://doi.org/10.5194/bg-17-4261-2020.

Harder, P., Schirmer, M., Pomeroy, J., and Helgason, W. 2016. ‘Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle’, *The Cryosphere* 10(6), pp. 2559–2571. Available at: https://doi.org/10.5194/tc-10-2559-2016.

Hargrove, W. and Pickering, J. 1992. ‘Pseudoreplication: A sine qua non for regional ecology’, *Landscape Ecology* 6, pp. 251–258. Available at: https://doi.org/10.1007/BF00129703.

Hasler, A., Geertsema, M., Foord, V., Gruber, S., and Noetzli, J. 2015. ‘The influence of surface characteristics, topography and continentality on mountain permafrost in British Columbia’, *The Cryosphere* 9(3), pp. 1025–1038. Available at: https://doi.org/10.5194/tc-9-1025-2015.

Heginbottom, J.A., Dubreuil, M.A., and Harker, P.T. 1995. ‘Canada, Permafrost’, in *National Atlas of Canada, 5th edition*. Natural Resources Canada, MCR 4177. Available at: https://doi.org/10.4095/294672.

Holloway, J.E. and Lewkowicz, A.G. 2019. ‘Half a century of discontinuous permafrost persistence and degradation in western Canada’, *Permafrost and Periglacial Processes* 31(1), pp. 85–96. Available at: https://doi.org/10.1002/ppp.2017.

Hrbáček, F., Oliva, M., Fernández, J.-R., Kňažková, M., and de Pablo, M.A. 2019. ‘Modelling ground thermal regime in bordering (dis)continuous permafrost environments’, *Environmental Research* 181, 108901. Available at: https://doi.org/10.1016/j.envres.2019.108901.

Jin, X.-Y., Jin, H.-J., Iwahana, G., Marchenko, S.S., Luo, D.-L., Li, X.-Y., and Liang, S.-H. 2021. “Impacts of climate-induced permafrost degradation on vegetation: A review’, *Advances in Climate Change Research* 12(1), pp. 29–47. Available at: https://doi.org/10.1016/j.accre.2020.07.002.

Joly, K., Gunn, A., Côté, S.D., Panzacchi, M., Adamczewski, J., Suitor, M.J., and Gurarie, E. 2021. ‘Caribou and reindeer migrations in the changing Arctic’, *Animal Migration* 8(1), pp. 156–167. Available at: https://doi.org/10.1515/ami-2020-0110.

Klene, A.E., Nelson, F.E., Shiklomanov, N.I., and Hinkel, K.M. 2001. ‘The N-factor in Natural Landscapes: Variability of Air and Soil-Surface Temperatures, Kuparuk River Basin, Alaska, U.S.A’, *Arctic, Antarctic, and Alpine Research* 33(2), pp. 140–148. Available at: https://doi.org/10.1080/15230430.2001.12003416.

Kropp, H., Loranty, M.M., Natali, S.M., Kholodov, A.L., Rocha, A.V., et al. 2020. ‘Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems’, *Environmental Research Letters* 16, 015001. Available at: https://doi.org/10.1088/1748-9326/abc994.

Lembrechts, J.J., Aalto, J., Ashcroft, M.B., De Frenne, P., Kopecký, M., et al. 2020. ‘SoilTemp: A global database of near-surface temperature’, *Global Change Biology* 26(11), pp. 6616–6629. Available at: https://doi.org/10.1111/gcb.15123.

Liu, L., Luo, D.-L., Wang, L., Huang, Y.-D., and Chen, F.-F. 2021. ‘Dynamics of freezing/thawing indices and frozen ground from 1900 to 2017 in the upper Brahmaputra River Basin, Tibetan Plateau’, *Advances in Climate Change Research* 12(1), pp. 6–17. Available at: https://doi.org/10.1016/j.accre.2020.10.003.

Mott, R., Vionnet, V., and Grünewald, T. 2018. ‘The Seasonal Snow Cover Dynamics: Review on Wind-Driven Coupling Processes’, *Frontiers in Earth Science* 6(197). Available at: https://doi.org/10.3389/feart.2018.00197.

Myers-Smith, I.H. and Hik, D.S. 2013. ‘Shrub canopies influence soil temperatures but not nutrient dynamics: An experimental test of tundra snow–shrub interactions’, *Ecology and Evolution* 3(11), pp. 3683–3700. Available at: https://doi.org/10.1002/ece3.710.

Myers-Smith, I.H. and Hik, D.S. 2018. 'Climate warming as a driver of tundra shrubline advance', *Journal of Ecology* 106(2), pp. 547–560. Available at: https://doi.org/10.1111/1365-2745.12817.

Nakagawa, S. and Cuthill, I.C. 2007. 'Effect size, confidence interval and statistical significance: A practical guide for biologists', *Biological Reviews* 82(4), pp. 591–605. Available at: https://doi.org/10.1111/j.1469-185X.2007.00027.x.

Odland, A., Bandekar, G., Hanssen-Bauer, I., and Sandvik, S.M. 2017. 'Relationships between vegetation, air and soil temperatures on Norwegian mountain summits', *Geografiska Annaler: Series A, Physical Geography* 99(4), pp. 313–326. Available at: https://doi.org/10.1080/04353676.2017.1333324.

Olefeldt, D., Heffernan, L., Jones, M.C., Sannel, A.B.K., Treat, C.C., and Turetsky, M.R. 2021. 'Permafrost Thaw in Northern Peatlands: Rapid Changes in Ecosystem and Landscape Functions', in J.G. Canadell and R.B. Jackson (eds.), *Ecosystem Collapse and Climate Change*. Switzerland: Springer, Cham, pp. 27–67. Available at: https://doi.org/10.1007/978-3-030-71330-0_3.

Philipp, M., Andreas, D., Buchelt, S., and Kuenzer, C. 2021. 'Trends in Satellite Earth Observation for Permafrost Related Analyses—A Review', *Remote Sensing* 13, 1217. Available at: https://doi.org/10.3390/rs13061217.

Riseborough, D., Shiklomanov, N., Etzelmüller, B., Gruber, S., and Marchenko, S. 2008. 'Recent advances in permafrost modelling', *Permafrost and Periglacial Processes* 19(2), pp. 137–156. Available at: https://doi.org/10.1002/ppp.615.

Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J., et al. 2015. 'Climate change and the permafrost carbon feedback', *Nature* 520, pp. 171–179. Available at: https://doi.org/10.1038/nature14338.

Șerban, R.-D., Bertoldi, G., Jin, H., Serban, M., Luo, D., and Li, X. 2023. 'Spatial variations in ground surface temperature at various scales on the northeastern Qinghai-Tibet Plateau, China', *CATENA* 222, 106811. Available at: https://doi.org/10.1016/j.catena.2022.106811.

Smith, M.W. and Riseborough, D.W. 2002. 'Climate and the limits of permafrost: A zonal analysis', *Permafrost and Periglacial Processes* 13(1), pp. 1–15. Available at: https://doi.org/10.1002/ppp.410.

Smith, S.L., Burgess, M.M., Riseborough, D., and Nixon, M.F. 2005. 'Recent trends from Canadian permafrost thermal monitoring network sites', *Permafrost and Periglacial Processes* 16(1), pp. 19–30. Available at: https://doi.org/10.1002/ppp.511.

Sturm, M., Holmgren, J., McFadden, J.P., Liston, G.E., Chapin, F.S., and Racine, C.H. 2001. 'Snow–Shrub Interactions in Arctic Tundra: A Hypothesis with Climatic Implications', *Journal of Climate* 14(3), pp. 336–344. Available at: https://doi.org/10.1175/1520-0442(2001)014<0336:SSIIAT>2.0.CO;2.

Suter, L., Streletskiy, D., and Shiklomanov, N. 2019. 'Assessment of the cost of climate change impacts on critical infrastructure in the circumpolar Arctic', *Polar Geography* 42(4), pp. 267–286. Available at: https://doi.org/10.1080/1088937X.2019.1686082.

Throop, J., Lewkowicz, A., and Smith, S. 2012. 'Climate and ground temperature relations at sites across the continuous and discontinuous permafrost zones, northern Canada', *Canadian Journal of Earth Sciences* 49(8), pp. 865–876. Available at: https://doi.org/10.1139/e11-075.

Tutton, R., Way, R.G., Beddoe, R., Zhang, Y. and Trant, A. 2021. 'Modelled Soil Temperature Sensitivity to Variable Snow and Vegetation Conditions in Low-Relief Coastal Mountains, Nunatsiavut and NunatuKavut, Labrador', in J. Zufelt (ed.), *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*. Reston, Virginia, United States: pp. 71–81. Available at: https://doi.org/10.1061/9780784483589.007.

Tyystjärvi, V.A., Niittynen, P., Kemppinen, J., Luoto, M., Rissanen, T., and Aalto, J. 2023. 'Variability and drivers of winter near-surface temperatures over boreal and tundra landscapes', *EGUsphere* [preprint]. Available at: https://doi.org/10.5194/egusphere-2023-576.

von Oppen, J,. Assmann, J.J., Bjorkman, A.D., Treier, U.A., Elberling, B., Nabe-Nielsen, J., and Normand, S. 2022. 'Cross-scale regulation of seasonal microclimate by vegetation and snow in the Arctic tundra', *Global Change Biology* 28(24), pp. 7296–7312. Available at: https://doi.org/10.1111/gcb.16426.

Walker, B., Wilcox, E.J., and Marsh, P. 2020. 'Accuracy assessment of late winter snow depth mapping for tundra environments using Structure-from-Motion photogrammetry', *Arctic Science* 7(3), pp. 588–604. Available at: https://doi.org/10.1139/as-2020-0006.

Wang, Y., Way, R.G., Beer, J., Forget, A., Tutton, R., and Purcell, M.C. 2023. 'Significant underestimation of peatland permafrost along the Labrador Sea coastline in northern Canada', *The Cryosphere* 17, pp. 63–78. Available at: https://doi.org/10.5194/tc-17-63-2023.

Way, R. and Lapalme, C. 2021. 'Does tall vegetation warm or cool the ground surface? Constraining the ground thermal impacts of upright vegetation in northern environments', *Environmental Research Letters* 16, 054077. Available at: https://doi.org/10.1088/1748-9326/abef31.

Way, R., Lewkowicz, A., and Zhang, Y. 2018. ‘Characteristics and fate of isolated permafrost patches in coastal Labrador, Canada’, *The Cryosphere* 12, pp. 2667–2688. Available at: https://doi.org/10.5194/tc-12-2667-2018.

Zhang, Y., Touzi, R., Feng, W., Hong, G., Lantz, T.C., and Kokelj, S.V. 2021. ‘Landscape-scale variations in near-surface soil temperature and active-layer thickness: Implications for high-resolution permafrost mapping’, *Permafrost and Periglacial Processes* 32(4), pp. 627–640. Available at: https://doi.org/10.1002/ppp.2104.