Responses to Reviewer's Comments for Manuscript egusphere-2025-620

In Situ Monitoring of Seasonally Frozen Ground Using Soil Freezing Characteristic Curve in Permittivity-Temperature Space

TC

Authors' Response to Reviewer 1

Reviewer #1's comment

This manuscript describes a comprehensive evaluation of soil moisture and soil temperature measurements at various locations in Canada with the aim of improving the classification of soils according to their freezing state. To this end, the authors consistently reconstructed and uniformly evaluated the freezing characteristic curve at 87 Canadian locations. This enabled them to determine where in Canada the soil is frozen for how long and how long the corresponding freezing and thawing phases last. Since the fundamental work of R.D. Miller and P.J. Williams & M.W. Smith in the 1970s and 1980s, the freezing processes of soils in relation to the phase change from liquid water to ice and the associated temperature and pressure changes have been relatively well understood. In the 1990s, several doctoral theses were written in Minnesota (E. Spaans), Zurich (D. Stadler), and Uppsala (M. Stähli), where the freezing characteristics of soils were measured—very similar to this work by Salmabadi—and then used in numerical models. Even back then, we had similar discussions to those we are having today: when exactly is soil "frozen"? And how relevant is this partially frozen state? I am very pleased that this topic is being addressed once again in this manuscript. Overall, I really like the study. The investigation of the freezing characteristics at the various Canadian locations is very thorough and undoubtedly adds value. As far as I can tell, the manuscript is linguistically flawless and well illustrated. Thank you very much.

Response:

We sincerely thank the reviewer for these kind words and for recognizing the value of revisiting this important topic. We appreciate the positive assessment of our work and the thorough evaluation provided.

Reviewer #1's comment

The methodology for the precise analysis of the freezing state based on the freezing characteristics is described in great detail and is easy to understand. I have hardly any questions or objections to this. Of course, one could perhaps be critical of the assumption in lines 144–145 that the total water content remains constant during the freezing process. We know that this is not the case, but that water is transported from lower soil layers to the freezing front. However, for the methodology used here, I do not think it is a major problem to accept this simplification. More decisive for me are the assumptions in section 2.5.1, a) that hourly values are ultimately aggregated to daily values and thus only determined on a daily basis whether the soil is frozen, partially frozen or unfrozen, and b) that the threshold values are set at p = 0.1 and 0.9 respectively. This makes sense to me, but I would still be curious to know whether there is a sensitivity analysis for these assumptions and threshold values.

Response:

We thank the reviewer for acknowledging that the assumption of constant total water content is an acceptable simplification for our methodology. We agree that water migration toward the freezing front occurs in reality; however, as the reviewer notes, this does not significantly affect the validity of our approach for characterizing the freezing dynamics within the monitored soil layer. We have clarified this assumption in the *Data Preprocessing* section and explicitly acknowledged it as a limitation in the *Discussion.*

Regarding temporal resolution, we confirm that all analyses were performed using *hourly* data, and the same temporal resolution is maintained in the final dataset that will be made publicly available. Aggregation to daily values was done solely for visualization and summarization purposes, providing a clearer overview of freezing patterns across networks.

Concerning threshold sensitivity, we agree that the initial thresholds ($p = 0.1$ for unfrozen and $p = 0.9$ for frozen) were somewhat arbitrary. We therefore conducted a sensitivity analysis to assess their influence. Based on the shape of the fitted SFCCs, we tested alternative thresholds of $p = 10^{-6}$ for unfrozen (representing a near-zero probability of freezing) and $p = 0.75$ for frozen. The aggregated daily results showed negligible changes when using $p = 0.75$ instead of $p = 0.9$, confirming that our classification and derived statistics are robust within reasonable threshold ranges.

Reviewer #1's comment

Now to the results. The various freezing curves measured at a total of 87 locations are pooled into four large regions. This is then used to make statements about how these large regions differ in terms of freezing and thawing. I find it relatively bold to make such broad regional statements based on such a small number of sensors, which also represent a very local scale and are unevenly distributed. Is it really justified to say that in the eastern boreal forest, soils typically freeze within a very small temperature range, while in the western boreal forest, freezing is more gradual?

Response:

We agree with this concern and thank the reviewer for highlighting it. In the original manuscript, we intended to caution readers against overgeneralizing our results across entire landscapes or biomes. However, as the reviewer correctly observed, presenting our findings by ecozone/land-cover type inadvertently conveyed a broader regional interpretation than warranted by the spatial density of our observations.

To address this, we have thoroughly revised the manuscript to avoid overgeneralization and ensure that results are described strictly at the network level.

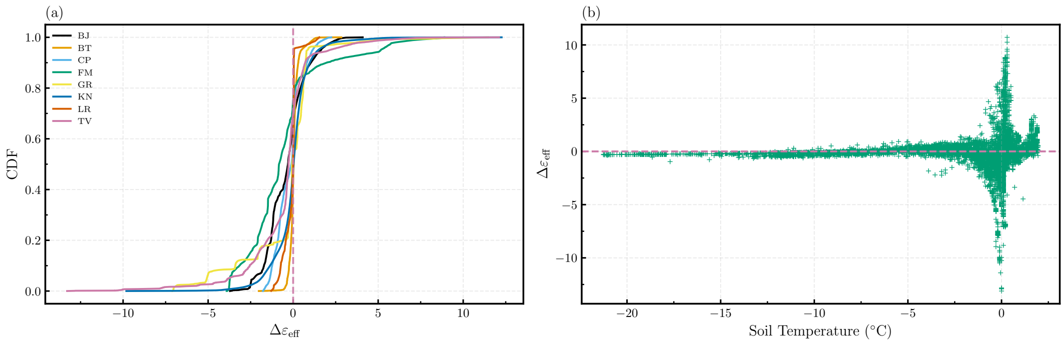
Changes made:

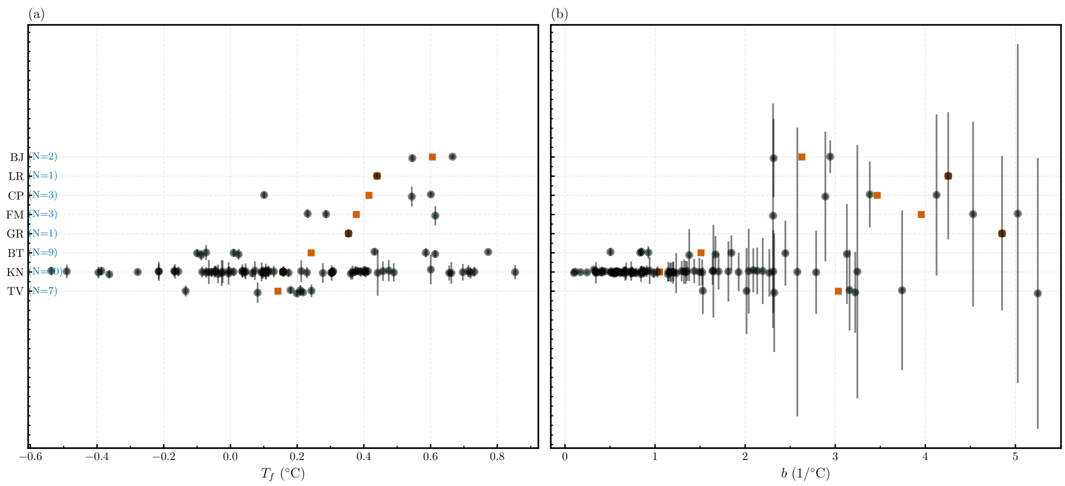
- **Restructured results presentation:** Results are now reported on a *network-by-network* basis rather than by ecozone/land-cover group. For instance, Table 2 has been updated to summarize curve fitting performance metrics for each network, and Figures 4 and 5 have been revised accordingly to reflect network-specific results.

Modified table in manuscript (Results):

~~Land Cover Type~~Network	R^2	RMSE	MAE
~~Eastern boreal forest~~ BJ	~~0.85~~ 0.93	~~1.25 (18.28~~1.20 (7.2%)	~~0.81 (11.85~~0.94 (5.7%)
~~Western boreal forest~~ BT	~~0.94~~ 0.95	0.29 (~~8.03~~3.7%)	0.18 (~~4.99~~2.3%)
~~Prairies~~ CP	0.82	0.80 (8.6%)	0.61 (6.6%)
FM	0.66	2.34 (11.7%)	1.70 (8.5%)
GR	0.67	2.13 (8.4%)	1.17 (4.6%)
KN	0.95	~~1.07 (10.94~~1.14 (3.8%)	~~0.65 (6.65~~0.71 (2.4%)
~~Tundra~~ LR	0.87	0.43 (7.4%)	0.25 (4.2%)
TV	0.86	~~1.71 (39.20~~2.07 (6.5%)	~~0.87 (19.94~~1.19 (3.8%)
Overall	0.95	~~1.16 (14.58~~1.26 (4.0%)	~~0.64 (8.05~~0.72 (2.3%)
Overall (balanced)	0.89	1.54 (4.9%)	0.86 (2.7%)

Modified figures in manuscript (Results):





- **Revised terminology throughout:** The Results section now explicitly refers to individual monitoring networks (e.g., "James Bay (BJ) network," "Candle Lake (BT) network") instead of broader regions such as "eastern boreal forest" or "western boreal forest." For example, the previous statement "eastern boreal forests freeze gradually" has been replaced by: "The James Bay (BJ), Montmorency Forest (FM), Chapleau (CP), and La Romaine (LR) networks, located within the eastern boreal forest ecozone, exhibit...," clarifying that our findings pertain to the specific monitored locations rather than the entire region.

Modified text in manuscript (Results):

To illustrate the application of our SFCC model (Eq. 4) and its integration with in situ data, we ~~presented five~~ present four example sites from different ~~monitoring networks , each exhibiting distinct freezing behaviors: eastern boreal forest (~~networks and ecozones, each representing a distinct freezing regime: EC17 from KN (prairie; Fig. ~~Fig. 7),~~ 6), BT17 from BT (western boreal forest~~(~~; Fig. 7), ~~prairie (~~BJ01 from BJ (eastern boreal forest; Fig. ~~9~~8), and ~~tundra (~~GR01 from GR (tundra; Fig. 9). Each example ~~consisted of~~ includes two panels: ~~the first panel~~panel (a) ~~depicted~~ shows the fitted SFCC overlaid on ~~the processed in situ measurements of~~ in situ soil temperature and ~~permittivity, with vertical lines indicating T_f and T_{res}. The second panel~~$\varepsilon_{\mathrm{eff}}$ measurements with T_f marked; panel (b) ~~displayed the~~ presents the corresponding time series of soil temperature~~for the same site, color-coded by the probability of frozen ground (degree of soil freezing). To further summarize the results, we included~~ , freezing probability, ERA5 air temperature, and IMS snow cover. To summarize all networks, Fig. 10 ~~, which shows the monthly average of the probability of frozen ground over the entire data period for all sites within each network. This visualization provided insight into the average freezing and thawing patterns at each station and network. In the eastern boreal forest, soils rarely freeze completely during winter (Fig. 10), reflecting high water retention and the insulating effect of snow and vegetation cover. This leads to either prolonged transitional states~~displays the monthly mean freezing probability, with monthly mean air and soil temperatures overlaid on each tile. To compare networks quantitatively, soil states were classified at hourly resolution as frozen if $P_{\mathrm{frozen}} > 0.75$, unfrozen if $P_{\mathrm{frozen}} < 10^{-6}$, and transitional (partially frozen) otherwise. Daily states were assigned by majority rule.

BJ, CP, FM, and LR~~— a phenomenon known as the zero curtain effect~~located in the eastern boreal forest~~— or unfrozen soil throughout the year. On average, we recorded 23 frozen days and 46 transitional days in this region~~remained predominantly unfrozen or partially frozen throughout the freezing season, with no periods of complete freezing despite persistent snow cover (> 90% from December to February) and subzero air temperatures. Their soils stayed near 0°C, yielding moderate freezing probabilities ($\lesssim 0.65$). For instance, FM and CP remained partially frozen for approximately 125 days, while BJ and LR showed shorter transitional periods ($\approx$ 100 days) with $\approx$ 75 unfrozen days. In contrast, ~~the western borealforest, characterized by drier conditions compared to its eastern counterpart, experiences more extensive freezing while still retaining some transitional states. On average, we recorded 73 frozen days and 76 transitional daysat these sites. As expected, tundra sites exhibited the longest frozen periods, with an average of 145 frozen days due to consistently low temperatures , along with 52 transitional days. Prairie soils began freezing earlier than boreal forest soils, likely due to the absence or shallow depth of snow cover and the lack of vegetation, as these sites are primarily agricultural lands. This lack of insulation made prairiesoils more susceptible to air temperature fluctuations (Fig 6) , allowing soil temperatures to drop more rapidly~~BT (western boreal) exhibited extensive freezing from December onward (90 frozen and 30 transitional days), coinciding with subzero air temperatures and complete snow cover. Tundra networks (TV, GR) recorded the coldest soil and air temperatures from December to February (soil and air consistently below −2 °C and −10 °C, respectively) and persistent snow cover ($\approx$ 100%), resulting in almost continuous frozen conditions (> 0.95) lasting 135 and 95 days for TV and GR respectively. The KN (prairie) network showed an intermediate response: although mean air temperatures ($\approx -3°C$) were comparable to eastern forest networks, soil cooling began earlier (November, $T_{soil} \approx 0.9\,°C$) and remained frozen through February (> 0.9) under shallow or intermittent snow ($50 - 95\%$). On average, ~~we recorded 71 frozen days and 71 transitional days in the prairies. Additionally, prairie soils thaw earlier than other landcover types, reflecting their sensitivity to air temperature variations~~about 70 days were classified as frozen and 60 days as transitional at KN. Overall, while all networks experienced similar subzero air temperatures and persistent snow cover from December to February, only tundra (TV, GR), western boreal (BT), and prairie (KN) networks exhibited sustained frozen states, whereas eastern forest networks (BJ, CP, LR, FM) remained largely in transitional or unfrozen conditions.

These revisions ensure that all results are contextualized appropriately to the spatial scale of the dataset and that no unintended regional generalizations remain in the text.

Reviewer #1's comment

This measured freezing behavior, which varies from location to location and from large region to large region, naturally has various causes, as explained in the discussion on line 365. It has a lot to do with soil properties, but also with the history (antecedent moisture content of the soil). However, when it comes to the question of "How many days per year is the soil frozen, partially frozen, or unfrozen?", two important factors come into play that are hardly discussed in the text: snow cover and air temperature. This aspect could be emphasized a little more in the manuscript. It would certainly be useful for the reader to learn more about the meteorological conditions and snow cover at the various measurement sites. Ultimately, the freezing curves are also influenced by these factors.

Response:

We greatly appreciate this valuable feedback. The reviewer is correct that snow cover and air temperature are among the most important environmental controls on soil freezing dynamics. These factors were underrepresented in the original version, and we have made substantial revisions to strengthen their treatment in the manuscript.

Changes made:

- **Expanded Introduction:** A new paragraph was added in the *Introduction* to expand the literature review and explicitly highlight the roles of air temperature, snow cover, and soil moisture as key controls on ground thermal regimes and soil freezing behavior.

  Modified text in manuscript (Introduction):

  > Beyond air temperature, which governs convective heat loss, soil freezing is primarily regulated by ground surface cover including snowpack, vegetation canopy and litter, moss, and organic (humus) layers as well as by soil moisture (MacKinney, 1929). Collectively, ground surface cover act as a thermal buffer, moderating soil–atmosphere heat exchange, conserving water, and reducing frost penetration (Fu et al., 2018). The insulating influence of snow, vegetation, litter, moss, and organic layers on soil temperature and moisture retention is well documented (Zhang, 2005; Decker et al., 2003; Flerchinger and Pierson, 1991; MacKinney, 1929; Gornall et al., 2007; Park et al., 2018; Lawrence et al., 2008; Oogathoo et al., 2022). Meanwhile, soil moisture exerts a dual control: its latent heat delays freezing onset, whereas ice formation increases thermal conductivity and accelerates subsequent cooling (Kersten, 1949; Lei et al., 2020).

- **Added ancillary datasets:** Two new datasets were integrated to provide environmental context for each network:
  - **IMS (Interactive Multisensor Snow and Ice Mapping System)** — daily snow cover at 4 km resolution.
  - **ERA5-Land** — hourly 2-meter air temperature at 0.25° resolution.

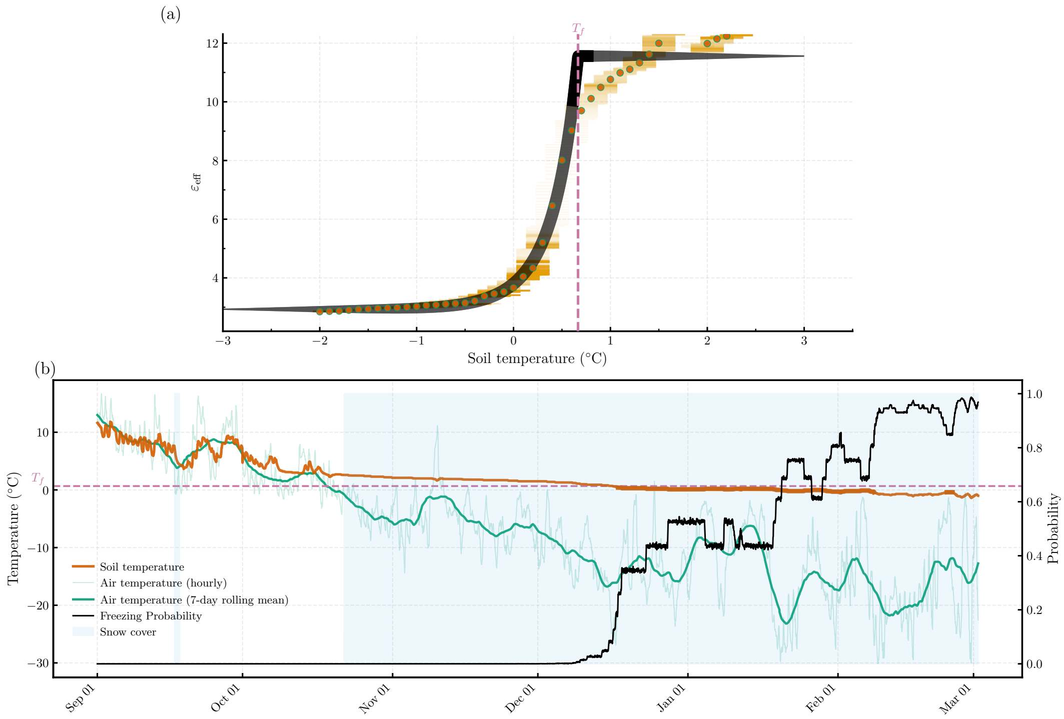
  These datasets were merged with the hourly in situ measurements to provide comprehensive meteorological information.

  Modified text in manuscript (Methodology):

  > Air temperature data were obtained from the ERA5-Land reanalysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF; (C3S, 2018)). ERA5-Land provides hourly 2 m air temperature at 0.25° spatial resolution and assimilates global observations within a physics-based numerical model to produce a consistent reanalysis extending from 1940 to the present. Snow cover data were derived from the Interactive Multisensor Snow and Ice Mapping System (IMS) produced by the U.S. National Ice Center (U.S. National Ice Center, 2004), which provides daily binary snow-cover maps for the Northern Hemisphere at 4 km resolution since 2004. The IMS product integrates multisensor satellite imagery and in situ observations. For each study site, snow-cover and air-temperature values were extracted from the corresponding IMS and ERA5-Land grid cells.

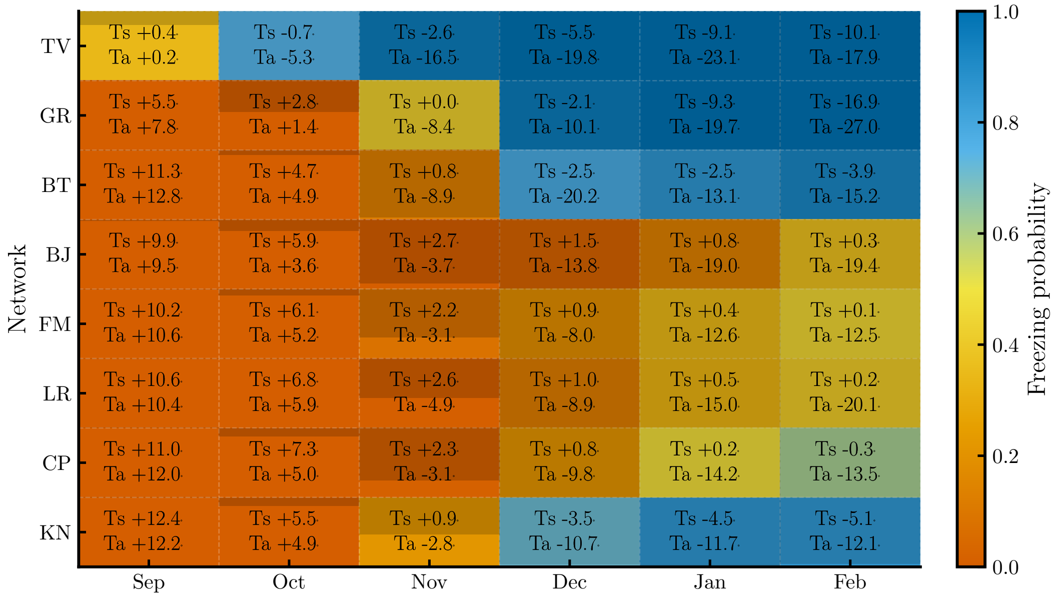
- **Enhanced figures:** Figures 6–9 were revised to include time series of ERA5-Land air temperature alongside soil temperature, and to indicate periods of snow cover derived from IMS data.

  Modified figure in manuscript (Results):



- **Revised network-level heatmap (Figure 10):** The network summary heatmap now displays monthly mean soil temperature, air temperature, and snow cover percentage, providing an integrated view of these controlling factors.

Modified figure in manuscript (Results):



- **Integrated into Results:** The section *Model Application to Field Data* now explicitly reports air temperature conditions, snow cover duration, and their relationships to the observed freezing probabilities for each network.
- **Expanded Discussion:** A new paragraph was added discussing how the combined effects of air temperature, snow cover, organic layer thickness, and soil moisture influence the freezing dynamics across our networks. This synthesis strengthens our interpretation of spatial differences in freezing behavior.

Modified text in manuscript (Discussion):

> Differences in soil freezing across the networks primarily reflect the combined effects of insulation and moisture rather than air temperature alone. Eastern boreal networks (BJ, FM, LR, and CP) remained largely unfrozen throughout winter due to thicker moss and organic layers, denser canopy cover, and higher soil moisture. These features collectively buffer ground heat loss, dampen temperature fluctuations, prolong the zero curtain phase, and keep the soil in a transitional state for extended periods. This interpretation aligns with modeling results from boreal forests in eastern Canada, where soils were shown to remain near 0°C throughout winter despite mean air temperatures around −16°C (Oogathoo et al., 2022; Lawrence et al., 2008). Such multilayer insulation reduces conductive and radiative heat exchange between the atmosphere and the soil, thereby limiting frost penetration even under severe cold conditions. In contrast, BT—a dry boreal network with sparse vegetation and thin organic horizons—and KN, which lacks vegetation and organic cover, exhibited earlier and deeper freezing. Tundra networks (GR and TV) experienced prolonged freezing driven by extreme cold and minimal insulation; soil freezing began almost immediately after air temperatures fell below 0°C, although GR's higher soil moisture delayed freeze onset relative to TV.

References

C3S. ERA5 hourly data on single levels from 1940 to present, 2018. URL `https://cds.climate.copernicus.eu/doi/10.24381/cds.adbb2d47`.

K. L. M. Decker, D. Wang, C. Waite, and T. Scherbatskoy. Snow Removal and Ambient Air Temperature Effects on Forest Soil Temperatures in Northern Vermont. *Soil Science Society of America Journal*, 67(4):1234–1242, July 2003. ISSN 03615995. doi: 10.2136/sssaj2003.1234. URL `http://doi.wiley.com/10.2136/sssaj2003.1234`.

G.N. Flerchinger and F.B. Pierson. Modeling plant canopy effects on variability of soil temperature and water. *Agricultural and Forest Meteorology*, 56(3-4):227–246, September 1991. ISSN 01681923. doi: 10.1016/0168-1923(91)90093-6. URL https://linkinghub.elsevier.com/retrieve/pii/0168192391900936.

Qiang Fu, Renjie Hou, Tianxiao Li, Ruiqi Jiang, Peiru Yan, Ziao Ma, and Zhaoqiang Zhou. Effects of soil water and heat relationship under various snow cover during freezing-thawing periods in Songnen Plain, China. *Scientific Reports*, 8(1):1325, January 2018. ISSN 2045-2322. doi: 10.1038/s41598-018-19467-y. URL https://www.nature.com/articles/s41598-018-19467-y.

J. L. Gornall, I. S. Jónsdóttir, S. J. Woodin, and R. Van Der Wal. Arctic mosses govern below-ground environment and ecosystem processes. *Oecologia*, 153(4):931–941, October 2007. ISSN 0029-8549, 1432-1939. doi: 10.1007/s00442-007-0785-0. URL http://link.springer.com/10.1007/s00442-007-0785-0.

Miles S. Kersten. Thermal Properties of Soils, June 1949. URL https://hdl.handle.net/11299/124271.

David M. Lawrence, Andrew G. Slater, Vladimir E. Romanovsky, and Dmitry J. Nicolsky. Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. *Journal of Geophysical Research: Earth Surface*, 113(F2):2007JF000883, June 2008. ISSN 0148-0227. doi: 10.1029/2007JF000883. URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2007JF000883.

Dawei Lei, Yugui Yang, Chengzheng Cai, Yong Chen, and Songhe Wang. The Modelling of Freezing Process in Saturated Soil Based on the Thermal-Hydro-Mechanical Multi-Physics Field Coupling Theory. *Water*, 12(10):2684, September 2020. ISSN 2073-4441. doi: 10.3390/w12102684. URL https://www.mdpi.com/2073-4441/12/10/2684.

A. L. MacKinney. Effects of Forest Litter on Soil Temperature and Soil Freezing in Autumn and Winter. *Ecology*, 10(3):312–321, July 1929. ISSN 0012-9658, 1939-9170. doi: 10.2307/1929507. URL https://esajournals.onlinelibrary.wiley.com/doi/10.2307/1929507.

Shalini Oogathoo, Daniel Houle, Louis Duchesne, and Daniel Kneeshaw. Evaluation of simulated soil moisture and temperature for a Canadian boreal forest. *Agricultural and Forest Meteorology*, 323:109078, August 2022. ISSN 01681923. doi: 10.1016/j.agrformet.2022.109078. URL https://linkinghub.elsevier.com/retrieve/pii/S0168192322002660.

Hotaek Park, Samuli Launiainen, Pavel Y. Konstantinov, Yoshihiro Iijima, and Alexander N. Fedorov. Modeling the Effect of Moss Cover on Soil Temperature and Carbon Fluxes at a Tundra Site in Northeastern Siberia. *Journal of Geophysical Research: Biogeosciences*, 123(9):3028–3044, September 2018. ISSN 2169-8953, 2169-8961. doi: 10.1029/2018JG004491. URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018JG004491.

U.S. National Ice Center. IMS Daily Northern Hemisphere Snow and Ice Analysis at 1 km, 4 km, and 24 km Resolutions, Version 1, 2004. URL https://nsidc.org/data/G02156/versions/1.

Tingjun Zhang. Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, 43(4):2004RG000157, December 2005. ISSN 8755-1209, 1944-9208. doi: 10.1029/2004RG000157. URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2004RG000157.