

Author Response to Review Comments

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Kilometer-scale distributed temperature sensing reveals heterogeneous permafrost warming near Arctic infrastructure

Response: We sincerely thank the Editor and the Reviewers for their thorough reviews of our manuscript and their constructive comments. Their suggestions have greatly improved the quality and clarity of the manuscript. Below, we provide a point-by-point response. Reviewer comments are shown in **black**, and our responses are shown in **blue**. Changes made in the revised manuscript are highlighted using track changes.

Response to Reviewer 1's Comments:

Great paper! Minor feedback.

Abstract: Concise, well written. Excellent to see such a long term study. Ready to read the paper.

Response: We thank the reviewer for the positive assessment of the abstract and for recognizing the value of the long-term dataset.

86-88 – Well set up to describe the novel data set and analysis presented in this paper.

Response: We thank the reviewer for the encouraging comment and are pleased that the novelty of the dataset and analysis is clearly conveyed.

99-100 – “A defining feature...” citation?

Response: Added citation in Line 100 “(Hu et al., 2017; Smith et al., 2022)”, and new reference in Line 899:

Smith, S. L., O'Neill, H. B., Isaksen, K., Noetzli, J., & Romanovsky, V. E.: The changing thermal state of permafrost. *Nature Reviews Earth & Environment*, 3(1), 10-23 (2022).

102-105 – “Although hysteresis has been recognized in observational and modeling studies, it is often treated implicitly rather than incorporated explicitly...” – Any more recent citations on this than 2003? Modeling has changed a lot.

Response: Added citation in Line 105 “; Westermann et al., 2013; Hu et al., 2017; Nicolsky et al.,

2017; Westermann et al., 2023; Jia et al., 2025”, and new references in the following lines:

Line 857: Jia, J., He, Z., & Tenorio, V. O. A hydrothermal coupling model for permafrost subgrade considering temperature gradient and its application. *Scientific Reports*, 15(1), 1816 (2025).

Line 885: Nicolsky, D. J., Romanovsky, V. E., Panda, S. K., Marchenko, S. S., & Muskett, R. R. Applicability of the ecosystem type approach to model permafrost dynamics across the Alaska North Slope. *Journal of Geophysical Research: Earth Surface*, 122(1), 50-75 (2017).

Line 930: Westermann, S., Schuler, T. V., Gislås, K., & Etzel Müller, B. Transient thermal modeling of permafrost conditions in Southern Norway. *The Cryosphere*, 7(2), 719-739 (2013).

109-111 – “A 2-km fiber-optic DTS array recorded continuous ground temperatures from 2021 to 2024 across civil infrastructure, non patterned tundra, and ice-wedge polygon terrain.” – AWESOME

Response: We sincerely thank the reviewer for the positive feedback.

117-119 – “The model reproduces observed permafrost temperatures, fills observational gaps, and enables projections of future ground temperatures under climate-change scenarios both along the DTS transect.” This sentence is a little confusing. Suggest rewording.

Response: Line 118 Sentence revised to be “By successfully reproducing observed permafrost temperatures and filling observational gaps, the model enables robust projections of future ground temperatures under climate-change scenarios along the DTS transect.”

140-144 – Confirming that 2 km of cable was installed one shovel width at a time?

Response: Yes, we confirm. The soil along the fiber-optic cable route was cut one shovel width at a time by hand, which minimized the influence of installation on the permafrost.

144-145 – So 1km of cable was installed, but the fiber was spliced upon itself to make 2km?

Response: 2 km of cable was installed and spliced at the far end of the route, producing a loop that yields a symmetrical 4-km dataset.

160-164 – Sentence is a bit long and mixes present and past tense. Might read more easily as two sentences.

Response: Line 166, the sentences are revised as follow: “DTS measurements provided temperature estimates at meter-scale spatial resolution along the entire transect. DTS data were recorded at 5-min intervals with a nominal temperature accuracy of ± 1 °C. Using a Raman-based DTS system, temperature is derived from the ratio of anti-Stokes to Stokes backscattered light along the fiber-optic cable.”

169-170 – Did you see drift? At 1-2km?

Response: There was drift over distance along the cable in the raw data. With double-ended measurements and calibration, the drift is corrected in the processed data.

173 – How were the in situ reference baths performed?

Response: DTS system has reference probes. Probe 2 was used for calibration, with a section of cable placed in the temperature-controlled laboratory facility where the DTS interrogator was housed. Please see Figure A1(b) displaying reference fiber sections.

176-177 – How often did the power interruptions and unstable sensors occur? What percentage of the data was removed? How much of the data was anomalous?

Response: We experienced power interruptions and sensor instability in the first month after cable installation; it was a small portion of the entire dataset. Most of the missing data is caused by storage issue, and it takes about 45% of the recording period, which is shown in Figure 5 as blank.

199-210 – so pressure only has a weak to moderate correlation and relative humidity negligibly correlates to wind speed.

Response: We agree with the reviewer’s accurate interpretation of the correlation analysis.

216-228 – did you come up with these equations?

Response: Yes. The equations (1) and (2) are the functional relationships between permafrost temperature with other input parameters.

258-259 – “The effects of precipitation...” is there a citation, or was this your own analysis?

Response: There is a citation. Line 268 Citation added “(Lin et al., 2003)”. The reference is already in the reference list.

308-310 – How many points are represented here? How many are in a, b, and c for Oct-Dec 22/23, Jan-May 24, and May-Sept23. Why are the dates broken up like that? 3 months, 5 months, 5 months?

Response: The dates are grouped due to different seasons, shown in the table below. This season grouping gives best correlation results. Number of data points are also shown in the table below.

Season	Period	a	b	c	Total
Freezing	Oct-Dec 22/23	6520	30523	10206	47250
Winter	Jan-May 24	11997	56163	18779	86940
Thawing	May-Sept 23	18779	87907	29393	136080
Total data points		37296	174593	58378	270270

332-340 – definitely helpful to have clarity in 144-145 to interpret this section.

Response: The diverse terrain and surface conditions traversed by the cable array are initially outlined in Lines 110–112. Furthermore, a detailed and precise landscape classification based on ground truth conditions and data interpretation is provided in the map-based Figure B2, copied below.

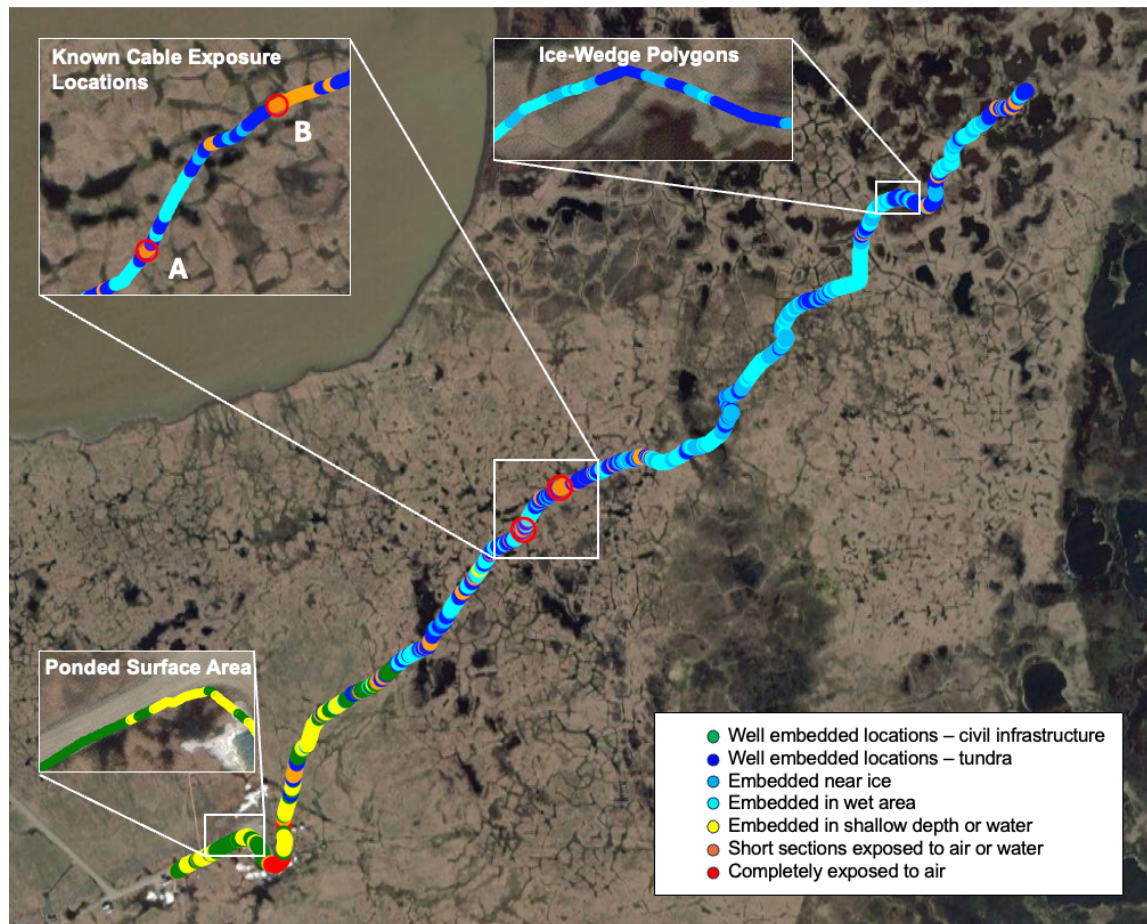


Figure B2. Permafrost location clusters based on permafrost temperature range and absolute offset with air temperature. Aerial maps are based on ArcGIS (Esri, 2020)

342-360 – In Figure 5, would be helpful to add thermometer readings / other validation to this somehow. In Figure 6, though a PDF can be zoomed in, it's still challenging to see the time series, particularly the yellow civil thermometer and the gray/purple tundra thermometer. Relatively, it does not look like the tundra thermometer agrees with the DTS? The legend is a tad confusing, are there many tundra thermometers? I see a lot of gray lines and a dark line that doesn't look like it's gray for purple/blue. Suggest updating this figure. Would be great to understand it better!!!

Response: Thermometer readings are point recordings. They are not comparable if added to Figure 5, because Figure 5 is temperature vs time vs length along the DTS cable. The used visualization used color bar, while thermometer readings are temperature vs time (single point). If added along the colormap figure, the comparison will not be obvious. Besides, the information would be duplicated with Figure 6.

We revised the legend of Figure 6 to make it clear. The thermometer readings were from four boreholes with limited duration as shown in the revised Figure 1 (copied below): one by the road

(civil infrastructure area), three in the tundra. The DTS temperatures of the two distinct areas in Figure 7 were averaged over the distance along the road and in the tundra, respectively, thus do not match the borehole thermometer readings; but they showed the same trend of temperature variation.

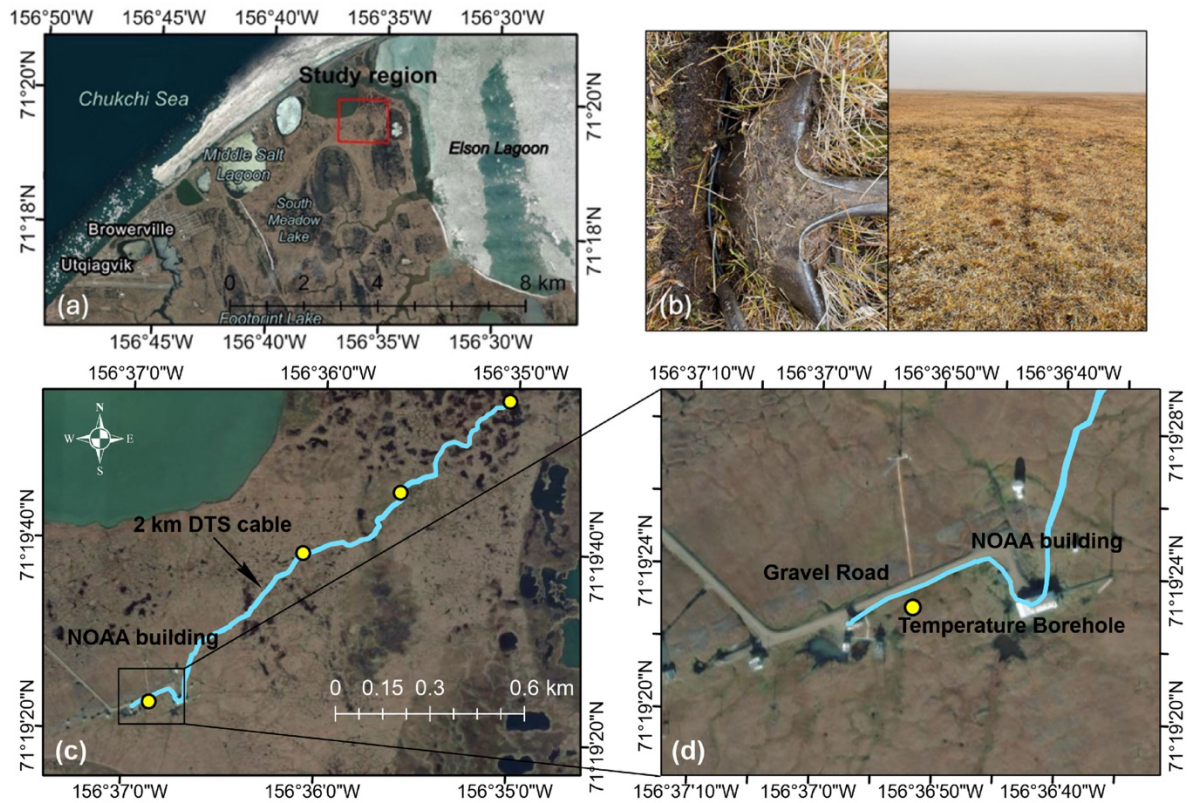


Figure 1. Maps of study region and DTS route in Utqiagvik, Alaska. Aerial maps are based on ArcGIS (Esri, 2020). Yellow dots represent the locations of boreholes with thermometers.

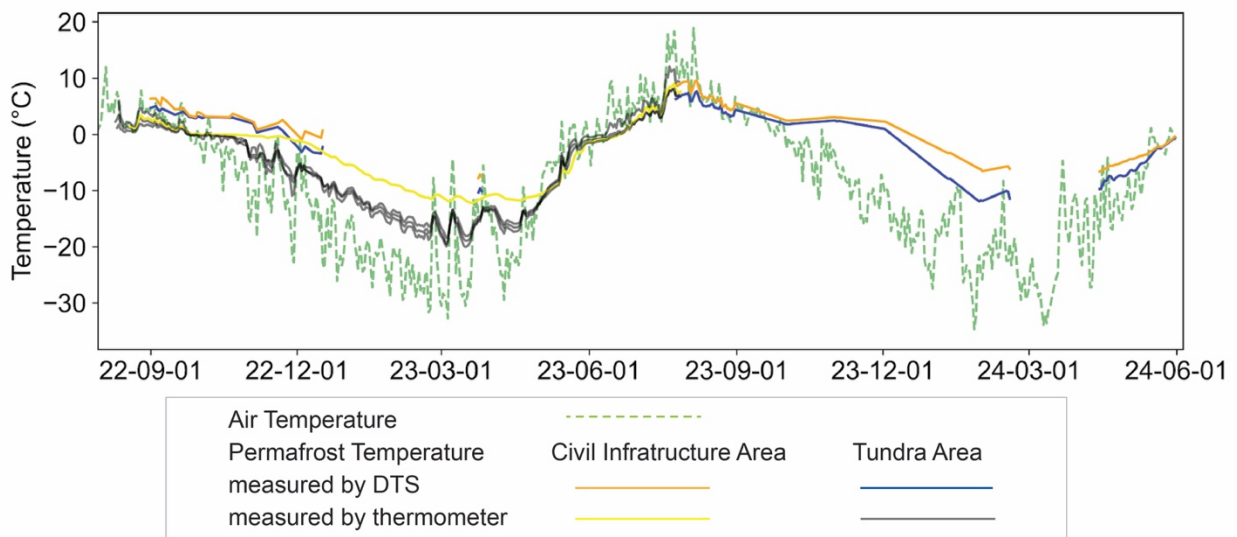


Figure 6. Comparison with air temperature, permafrost temperature measurements obtained from DTS in both the civil infrastructure and tundra areas, and thermometer recordings at depth of 0.15 m at four locations. The DTS results closely align with the thermometer readings, validating the reliability of the DTS method.

364-369 – would be neat if you had a figure showing this geospatially.

Response: The data illustrated in Lines 374 – 379 are regional averaged temperature difference, derived from Figure 6; thus, the data cannot be presented geospatially. The temperature difference between civil infrastructure area and tundra area is visualized geospatially in Figure 11(a) and (d).

371-382 – Different time periods selected than 308-310. These periods are explained in this section (excellent!). Leads back to the 308-310 question of why that time breakout? Figure 7 – not sure I understand the arrows. Freezing is happening below -5 and thawing above -2.5? Could something be thawing from -5 to 15? Could something be freezing from 0 down to -25?

Response: We break the temperatures into three distinct seasons: Oct to Feb of the next year is the ground freezing season, Mar to May is the season with relatively stable ground temperature, and Jun to Sep is the ground thawing season. Different data points of the same marker (such as black circles) represent different time in the same season. The arrows in Figure 7 (copied below) represent the permafrost temperature variation trends. Ground thawing is characterized by faster transition, while ground freezing experiences gradual process due to the asymmetric latent heat exchanged in the phase change. The figure also clearly reveals that ground temperatures in infrastructure area are consistently higher than those in the tundra throughout the recording period.

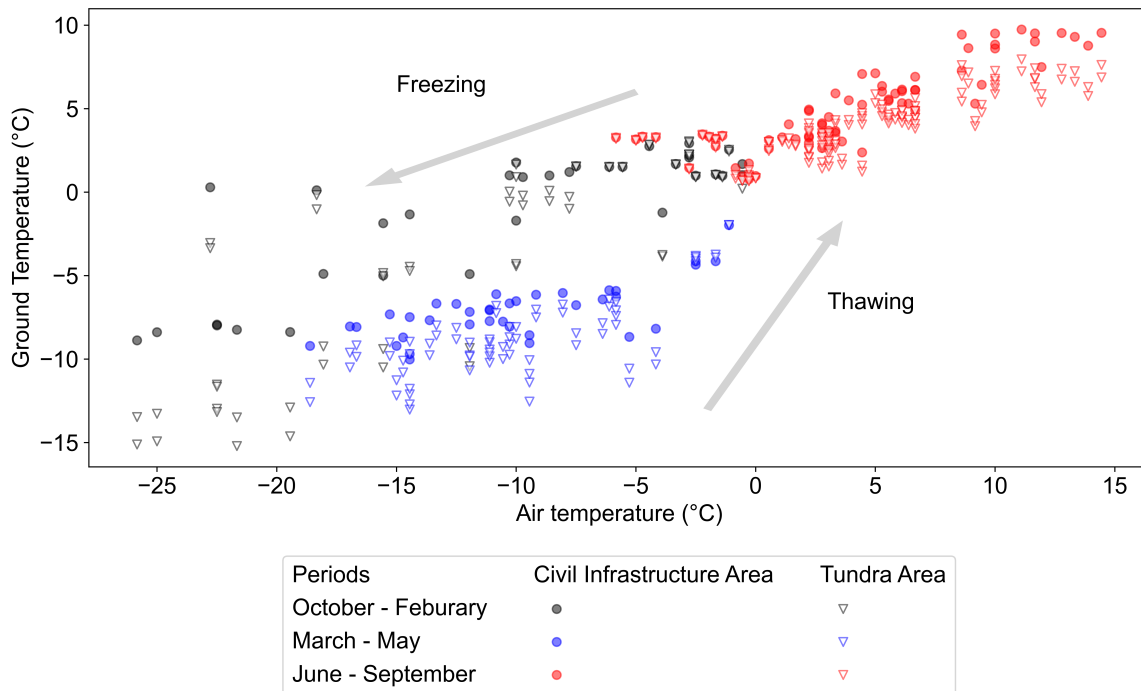


Figure 7. Ground temperature and air temperature comparison from September 2022 to May 2024 in civil infrastructure area and tundra area.

397-400 – would be neat to know what the warmer spots (particularly in b) are attributed to.. could add a text box in the fig depending on the reason.

Response: The warmer spots are associated with polygon centers. This was added to Figure 8 caption.

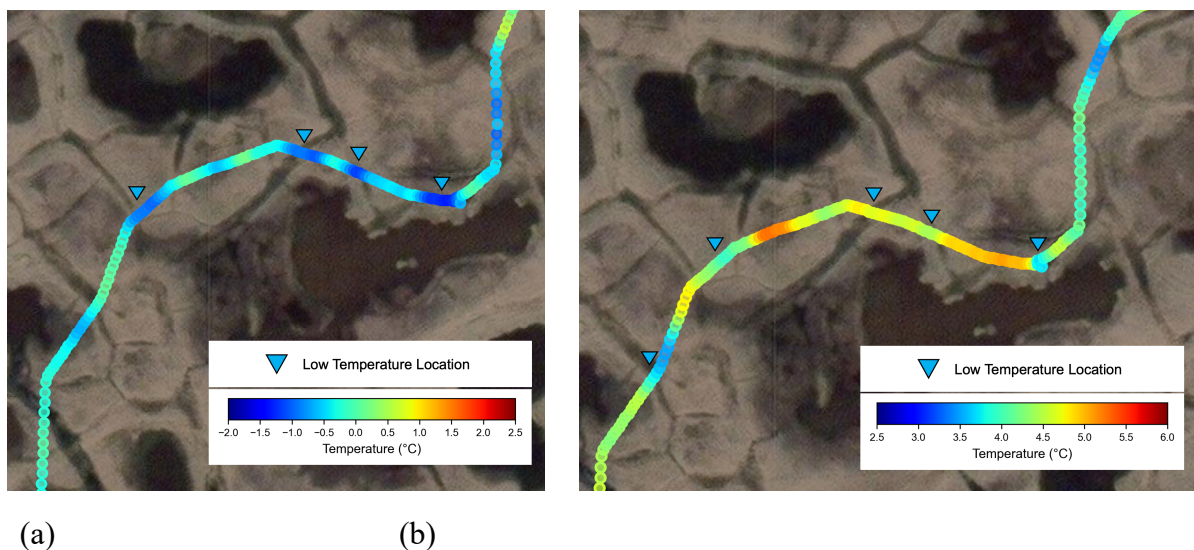


Figure 8. Ground temperatures in ice-wedge polygon region along fiber 1560 m – 1730 m in

December 2022 (a), and July 2023 (b). Warmer spots are associated with polygon centers. Aerial maps are based on ArcGIS (Esri, 2020)

415-419 – nice!

421-423 – Excellent Fig. clearly shows impact of infrastructure.

447-450 – Figure 10 is important. Suggest overlaying horizontal lines / zones where the model has filled in the missing information. It would be easier for the reader to see how challenging it might have been for the model to match up with measured data.

Response: Horizontal lines with arrows were added to Figure 10 (copied below). The arrows show the time windows with missing temperature data that were reproduced by the model.

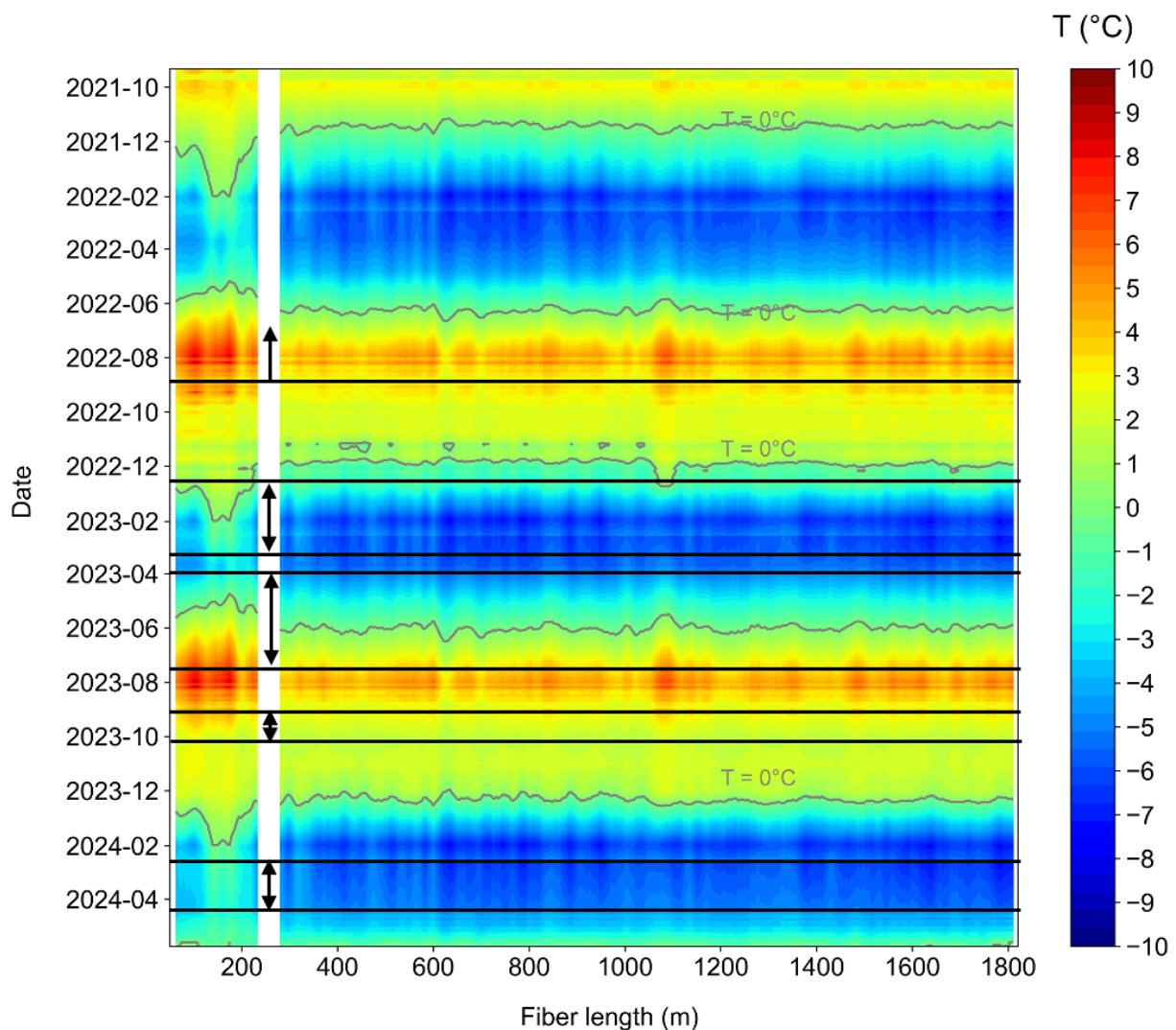


Figure 10. Complete spatiotemporal ground temperature profile at the permafrost table based on

DTS measurements and hysteresis model predictions. The vertical blank strip is the section where DTS cable is attached to a building above ground. The arrows show the time windows with missing temperature data that were reproduced by the model.

467-476 – Figure 10, great fig

501-513 – Interesting. Is there any engineering work to point to that would make linear infrastructure less influential?

Response: Linear infrastructure can indeed be engineered to minimize its thermal impact on the underlying permafrost through both passive and active cooling techniques.

To address the reviewer's point, we have expanded our discussion in Lines 516–520 to highlight proven engineering methodologies.

Sentence added: “To minimize the thermal degradation of underlying permafrost, linear infrastructure engineering utilizes passive and active mitigation strategies, such as two-phase thermosyphons, air-convection rock embankments, and thermal insulation arrays, to dynamically extract subsurface heat and shield the ground from atmospheric warming (Arenson et al., 2015; Doré et al., 2016; Fazilova, 2020).”

Reference added:

Line 807: Arenson, L. U., Johnston, K., Quinn, P., & Wainstein, P. Considering permafrost in the design of linear infrastructure through mountainous terrain. In *Joint 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference*. Canadian Geotechnical Society (2015).

Line 836: Doré, G., Niu, F., & Brooks, H. Adaptation methods for transportation infrastructure built on degrading permafrost. *Permafrost and Periglacial Processes*, 27(4), 352-364 (2016).

Line 844: Fazilova, Z. Construction and operation of linear constructions at the polygonal land relief, in the conditions of distribution of permafrost soil. In *IOP Conference Series: Materials Science and Engineering* (Vol. 919, No. 2, p. 022029). IOP Publishing. (2020, September).

530-544 – would be nice to highlight a more temperature volatile period the model successfully produced.

Response: Lines 551 – 553 added: “The predictive model successfully captured abrupt subsurface thermal transitions during freezing and thawing, demonstrating its capacity to handle intense environmental dynamics rather than just stable seasonal trends.”

605-610 – Does this work continue? Can you project to 2030 and then cross check your predictions

in a few years?

Response: The DTS cable is still embedded in place in the tundra. However, the DTS interrogator was removed since it was rented. There is potential opportunity to continue to monitor the future ground temperatures of the tundra if funding is available.

743-745 – Figure B2 is GREAT. Would be help to do something like this for 397-400

Response: Similar figures were generated for each month but are omitted from the manuscript due to space constraints; however, representative visualizations and trends can be observed in Figures 11(a) and (d).

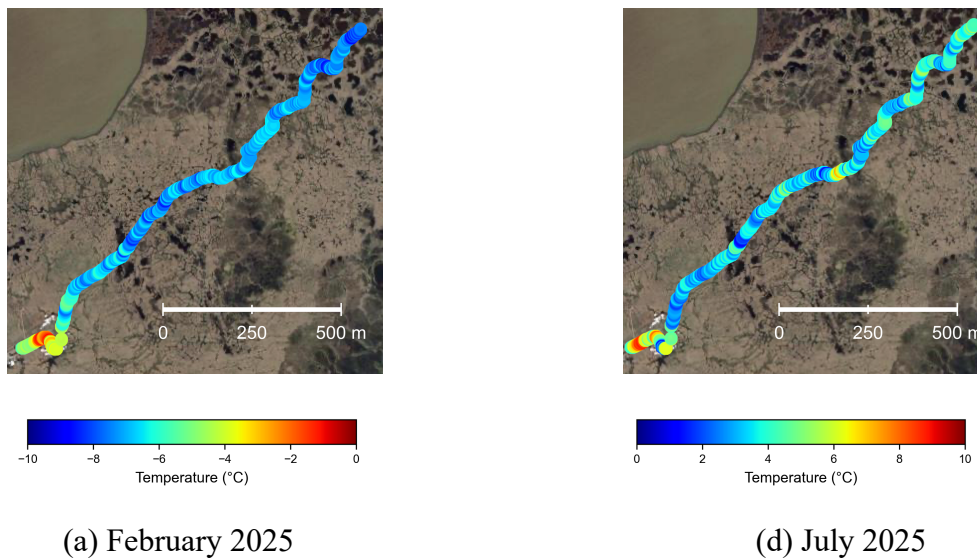


Figure 11. Permafrost temperature predictions under RCP 4.5 and RCP 8.5 along the DTS cable route. Aerial maps are based on ArcGIS (Esri, 2020)

752-756 – Again – curious about why those time periods. Confusing figs

Response: Please see earlier response to comments regarding lines 308-310.