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 2's Comments:

This nicely done study represents one of the few long term applications of fiber-optic distributed temperature (FO-DTS) sensing to the monitoring of fine scale soil temperature patterns in cold regions. While the manuscript is generally well-written and organized, I do not believe the authors make a strong case as to defining compelling and transferrable research objectives framed around process understanding. Instead, too much of the focus seems to be in gap-filling missing (some substantial) FO-DTS data chunks, which is a hyper-local application and bends the paper toward a case study application. The transferrable value of the study comes out in the latter results and discussion sections, but needs some better framing up front to help keep the reader engaged. I have also listed a range of suggestions, more major or minor, below for consideration in a revision.

Response: We sincerely thank the reviewer for the positive assessment of our work as "one of the few long-term applications of fiber-optic distributed temperature sensing (FO-DTS)" in cold regions.

We agree with the reviewer's insight that the transferrable value of our study lies in its broader process understanding. To better align the manuscript with transferrable process understanding and properly balance this technical baseline with our scientific insights, we have thoroughly revised the framing in the Introduction and Methodology sections as follows:

1. We have rewritten the objectives in the Introduction to center explicitly on how high-density spatial observations decode localized thermal lag and thermal offset mechanisms across diverse terrains.
2. We have condensed the technical implementation details of the data-gap remediation in the main text. This preserves the operational transparency required for other Arctic DTS

practitioners without distracting the reader from the core scientific findings.

3. We have expanded the latter sections of the manuscript to directly tie our model's performance back to transferrable cold-regions applications.

We believe these structural adjustments significantly strengthen both the technical and scientific merit of our study. However, we would like to clarify that what might initially appear to be site-specific practical issues, such as prolonged data outages due to extreme conditions or the inability to maintain calibration baths between annual field visits, are pervasive major hurdles that nearly all long-duration Arctic distributed fiber optic sensing operations would encounter. Consequently, the data remediation methodologies and quality control workflow presented here fill a critical global gap in cold-region experimental capabilities and provide a necessary framework to achieve high-resolution, long-duration temperature measurements under extreme field conditions.

Detailed responses to each of your specific major and minor suggestions are provided below.

More major points:

-Clear research questions or hypotheses are needed at the end of the introduction section. As stated, it seems like a lot of work was done to fill gaps in soil temperature monitoring data for one case study that might have limited transferability to other sites. Section 3.3 feels very much like the aim of an isolated case study or site characterization, not broadly useful research on soil temp controls in permafrost areas. In section 4.4, it would be good to reinforce for the reader why this gap filling of measured soil temperatures is necessary and how it adds to the transferrable research aspects of this study. Is the more important use as a statical model to test projected warming scenarios on soil temperature under varied land cover/use? Other studies have already broadly shown soil warming in transitional permafrost areas where infrastructure is added and natural vegetation disturbed (including local changes in ground shading). Perhaps a more novel and is based on section "4.3 Meter-scale thermal heterogeneity associated with ice-wedge polygon microtopography" as monitored with FODTS. That is the most scientifically interesting section of the manuscript, IMO. Can you dive deeper into the potential drivers of the non-patterned vegetation areas having the coolest relative soil temperatures? Ie Consider speculating as to whether this is attributable to lower surface water, vegetation type, or shallower active layer. Do you have any additional active layer thickness data distributed along the DTS line at point(s) in time?

Response: A paragraph is added in the Introduction section in Lines 108 – 120: "The primary purpose of this study is to advance high-resolution permafrost modeling capabilities by developing a transferrable, data-driven framework that bridges the gap between highly localized linear observations and regional-scale predictive mapping. Specifically, this research aims to achieve three core objectives:

1. To evaluate how distinct landscape variations, including civil infrastructure, non-patterned tundra, and ice-wedge polygon terrain, differentially alter subsurface thermal regimes and drive microclimatic heterogeneity.
2. To establish a robust data-remediation framework capable of reconstructing high-resolution, long-duration data baselines for reliable cold-regions predictive modeling.
3. To capture and explicitly parameterize the non-linear thermal hysteresis and time-lagged responses between air and ground temperatures, providing a foundational modeling framework that can be scaled regionally using sparse borehole networks."

The purpose of Section 3.3 is to provide permafrost temperature predictions based on the newly proposed model, as a foundation of later regional predictions.

In Section 4.4, multiple sentences are added:
Lines 452 - 458: "The multivariate hysteresis model successfully reconstructs missing DTS observations and captures seasonal freeze–thaw behaviors across the transect, filling a critical gap in long-duration Arctic observational capabilities where prolonged instrumental outages are a pervasive hurdle. Fig. 10 presents a complete temperature profile from September 2021 to May 2024, with data gaps filled by model estimates. Remediating these multi-month data gaps is a prerequisite for scaling predictive frameworks regionally; continuous, gap-free baseline datasets are essential to accurately train and validate models intended for borehole-based regional permafrost mapping".
Lines 477 - 479: "Ultimately, by proving that a data-driven framework can accurately resolve these complex thermal gaps across diverse terrains, this approach offers a transferrable methodology for maximizing the utility of sparse, real-world Arctic climate records".

We agree with the reviewer's excellent point that the true novelty and primary value of our framework lie in its capacity to serve as a robust, data-driven predictive tool. Previous research is more qualitative analysis. Our work shows the model ability to estimate and predict the warming effect quantitatively. It can reliably simulate how diverse land-cover types (disturbed vs. undisturbed) will respond to future, highly sensitive climate warming scenarios. To align the manuscript with this perspective, we have downplayed the "observation of infrastructure warming" as our primary finding, re-framing it instead as the vital baseline calibration data that proves our model's fidelity in the Introduction section.

A new paragraph is added in Lines 439 – 450: "The relatively lower soil temperatures observed in non-patterned vegetation areas are likely attributed to distinct surface-subsurface ecohydrological mechanisms. First, non-patterned tundra typically features a well-developed, continuous layer of organic mosses and lichens. This vegetation type provides significant ground shading during the summer months while maintaining a low thermal conductivity when dry, acting as an insulating barrier against atmospheric heat penetration. Second, the absence of polygonal microtopography prevents the accumulation of ponded surface water, which is common in ice-wedge polygonal terrains. Because water has a high thermal conductivity compared to dry organic matter, the lower surface water content in non-patterned areas limits advective and conductive heat transfers into the ground. Consequently, these combined insulation and moisture dynamics maintain a cooler thermal profile throughout the thaw season, leading to a shallower active layer that acts as a negative feedback loop to preserve cold subsurface conditions".

- Section 3.2 states: "To model permafrost temperature dynamics and reconstruct missing DTS observations, we developed a non-linear, multivariate hysteresis-based framework that explicitly represents the asymmetric, lagged relationship between air temperature and ground temperature, while considering meteorological factors and ground surface conditions. (FODTS cable)". However, earlier, it is stated that "…burial depths of approximately 20 to 40 cm" . Buried FODTS deployments are tricky as the exact sediment depth is often a strong control on the measured temperature, especially in evaluating time lags from air or the land surface. Given the depth of burial here varied by up to 100%, I would expect large uncertainty to propagate into the statistical modeling, unless data were selected from sections of known common depth when assessing air to ground temp signal time lags. Please explain your approach in more detail related to this concern.

Response: We thank the reviewer for highlighting the practical challenges of evaluating time lags in buried FO-DTS systems. The reviewer is correct that if a cable varies in depth, a uniform or generalized model would have uncertainty propagation due to differing thermal damping rates. During DTS cable installation, the cable was positioned at the permafrost table, which varied from approximately 20 to 40 cm below ground surface. Thus, the burial depths varied.

To clarify our approach, we would like to highlight two critical aspects of our experimental setup and modeling framework that turn this challenge into a core capability of our system:

1. The cable was not buried at an arbitrary static depth; rather, it was deployed **directly on top of the permafrost layer** (illustrated in Lines 152 – 154). In Arctic landscapes, the depth of the permafrost table naturally fluctuates spatially (here, between 20 and 40 cm) due to microtopography and vegetation. By placing the cable exactly on this boundary interface, we ensure it measures the highly critical active layer-permafrost thermal transition zone across the entire transect.
2. **Meter-by-meter (channel-specific) individual parameterization:** Our multivariate hysteresis model does not treat the 2-km transect as a single bulk dataset. We calculate a separate, unique set of model parameters independently for every single meter along the array. Because every single meter has its own custom-fit parameters, the model natively

adapts to the unique environmental signature of that exact spatial coordinate. It implicitly accommodates the precise lag time, and other fitting parameters governed by the specific burial depth and soil properties of that individual pixel. This localized training eliminates the risk of macro-scale uncertainty propagation. We have updated Section 3.2 (Lines 213–219) to explicitly detail this point-specific modeling architecture for the reader.

-I would expect soil moisture to be one of the strongest local controls on heat exchange at a given depth. It does not seem that was measured here, which would have been quite difficult to accomplish along the cable without active heating FODTS methods. I do not believe this is a fundamental flaw of the study, but the topic deserves some discussion and summary of related literature. Beyond advective heat exchange due to percolation of precipitation, soil moisture is a primary control on unsaturated soil thermal diffusivity.

Response: We agree that a robust discussion of moisture content significantly improves the scientific rigor of our manuscript. As the reviewer noted, measuring high-resolution soil moisture continuously over multiple years along a 2-km transect is practically unfeasible without active-heating FO-DTS methods. To address this comment, we have expanded our discussion in Section [3.2] (Lines 331–350) to explore the scientific implications of soil moisture from both a physical and statistical modeling standpoint, with the following key points:

1. **Implicit Modeling of Hydro-Thermal Dynamics:** Physically, soil moisture is non-linearly dependent on ground temperature (governed by ice-water phase transitions and latent heat effects), alongside precipitation, snow cover, and landscape microtopography. Because our multivariate hysteresis framework utilizes a meter-by-meter individual optimization structure, each localized sub-model implicitly learns the characteristic thermal diffusivity variations, scaling effects, and moisture-driven lag signatures unique to that specific spatial coordinate.
2. **High Accuracy Without Saturated Inputs:** Our cross-validation results demonstrate that despite missing explicit soil moisture as a direct input, the data-driven model successfully captures the thermal heterogeneity and freeze-thaw timing along the full transect. This indicates that the meteorological drivers and point-specific calibration serve as effective proxies for these localized environmental dynamics.
3. **Maximizing Regional Transferability:** Scientifically, while soil moisture is a critical physical parameter, most globally existing regional permafrost boreholes only measure temperature profiles—they lack continuous soil moisture monitoring. This enables the model to be directly scaled up to regional-scale predictive mapping using sparse, real-world borehole networks that are common in polar science.

-It is not clear what data were used to create the statistical models described in section 3.2. Is that all based on local MET obs and FODTS data from times when the system was fully functional?

Response: Only FO-DTS data is used for the statistical model. Added sentence in Lines 213 – 215: "The model is trained, calibrated, and optimized independently for each individual spatial channel along the DTS cable, using calibrated DTS data".

-The FODTS instrument type/manufacturer needs to be listed in the methods section. Also, the text states that double ended measurements increase data accuracy. That is not necessarily the case. In double ended mode in the current setup, data collected 2 km further out along a given fiber as a given location, but at the same spatial location due to the fiber loop, are folded onto the data collected nearer to the control unit. Data collected multiple km further out are inherently nosier due to signal loss with distance. So that near and far data averaging process actually decreases the precision (and possibly accuracy) of the near field data. Double ended mode is most important in accounting for step changes in signal loss around fiber splices, which is not accounted for, will decrease measurement accuracy. Also, more detail is needed on how the reference baths were setup.

Response: The FODTS instrument type/manufacturer is added in Line 181: "(Oryx DTS OX4-SR)".

We agree with the reviewer's point of double-ended calibration. To address the reviewer's concern and clarify our handling of this precision-accuracy trade-off, we have updated Section [3.1]:
Lines 182 – 185: "The DTS data were calibrated using a double-ended configuration to explicitly compensate for spatially variable differential attenuation and localized step losses, which are particularly pronounced at cable splices, connectors, and sharp terrain-transition bends".
Lines 214–221: "Double-ended calibration mathematically combines low-attenuation (near-field) signals with high-attenuation, noisier (far-field) signals for any given physical location. It can inherently propagate far-field noise and degrade the baseline precision of the near-field data. To mitigate this precision-accuracy trade-off, we implemented a robust temporal integration window (5-minute averaging) which successfully suppressed the high-frequency optical noise floor. By prioritizing the elimination of localized spatial step-loss biases thus maximizing accuracy over minor high-frequency precision losses, the calibrated dataset provides a highly stable and physically accurate thermal baseline for the subsequent hysteresis modeling."

For reference section setup, please see Lines 746 – 749. Added sentence in Line 748: "Probe 2 (labeled in Figure A1(b)) is indoor temperature of DOE lab facility where the interrogator was housed".

-L178 and elsewhere: Why was it necessary to estimate missing FODTS data chunks using the model? I am not sure that improved the scientific understanding of the heat exchange processes at hand.

Response: We agree that in an ideal scenario of instrumental uptime, estimating missing data would not add direct value to our physical understanding of heat exchange. However, in the real-world applications, continuous long-term monitoring is heavily affected by environmental equipment failures, power outages, and communication losses. This results in highly fragmented datasets. The scientific necessity and transferrable value of our reconstruction approach lie in three key areas:

1. Preventing Bias in Machine Learning / Regional Upscaling: Most regional permafrost models that scale borehole data to broader regional maps require continuous, gap-free training inputs. Utilizing a gappy dataset introduces mathematical bias. Our framework demonstrates how to "rescue" incomplete field measurements to generate robust, gap-free training sets.
2. Validation of Process-Level Understanding: The fact that our hysteresis model can seamlessly fill these multi-month gaps and align with observed data during recovery periods is a physical finding. It proves that the model has successfully captured the core, non-linear thermal-lag dynamics (the physical relationship between air temperature, snow, and permafrost). If the model lacked physical accuracy, the reconstructed segments would not match the real-world boundaries upon system recovery.

-FODTS data precision increases with time, and data (in this case 5-min) can be stacked after data collection to improve precision. Why was that not done here to achieve better resolution? It seems odd that all data are reported to the nearest whole number, which is atypical of FODTS data, and seems to under-utilize the capability of the technology, especially in nuanced, complex terrain.

Response: During calibration, each DTS data file is calibrated separately, corresponding to the original 5-min interval. For the model usage, estimation and prediction, the DTS data is stacked per day. Phrase added in Line 231: "DTS data stacked as daily averages." No data in the manuscript is reported to the nearest whole number. All the tick marks of figure's temperature axis are whole number, and the data reported in manuscript are rounded to the nearest 0.1 °C.

- L342 and following paragraph: Why do the FODTS data need to be 'validated'? FODTS instruments are advanced, high tech methods for measuring temperature. Do you have reason to believe your calibration of the data for offset over time or the dual ended calculations were flawed? As borehole and FODTS data are never truly co-located, the fact your FODTS instrument integrated soil temperature over 1 m linear spatial scales, and the fact temperature is often highly variable in the subsurface, it can be difficult to 'validate' in this way. FO-DTS has been used for environmental monitoring for at least 20 years, so there seems little need to broadly 'validate' the reliability of the technology, so you may want to reword the final sentence in this paragraph. Also, what do you mean (quantitatively) by "closely align"?

Response: The word "validated" was used incorrectly and caused confusion. Line 410 "validated by" is replaced by "compared with". The last sentence of this paragraph is deleted.

- I am wondering how much of this story is local vegetation shading related vs infrastructure per se. Section 4.2 is titled "Infrastructure-related permafrost warming" (though it seems we are talking about active layer warming), though I am reminded of this study (doi: 10.1002/2014GL059251) and others that showed a strong local control on permafrost persistence based on the shading of individual clusters of bush vegetation in transitional permafrost areas.

Response: We thank the reviewer for raising this critical physical and spatial aspect and appreciate the connection to the mechanisms detailed in Briggs et al. (2014).

Our FO-DTS cable is deployed directly along the boundary between the active layer and the permafrost layer (the permafrost table), it is uniquely positioned to measure the exact depth where surface-driven thermal changes determine permafrost stability. Besides, our FO-DTS cable in the infrastructure area was not buried directly underneath the gravel road embankment. Rather, it was deployed along the permafrost table adjacent to the road, beneath a layer of native tundra vegetation that is thinned compared to the pristine, undisturbed tundra further away. This specific setup means we are measuring a highly localized permafrost "edge effect", which directly relates to the micro-climatic controls discussed in Briggs et al. (2014). We have updated Section 4.2 (Lines 455–469) to discuss this coupled thermal regime of infrastructure area:

1. Direct physical effect: The altered thermal properties (conduction and albedo) of the infrastructure materials themselves.
2. Indirect ecological effect due to vertical shading reduction and lateral thermal and physical influences. Directly above the DTS cable, the tundra vegetation canopy is present but thinned (due to dust deposition, runoff alteration, or historical construction disturbance). This thinned organic mat provides less vertical insulation and micro-shading, allowing greater summer heat penetration to the permafrost table, the exact inverse of the localized vegetation-shading preservation highlighted by Briggs et al. (2014). Laterally, the nearby gravel embankment absorbs substantial summer solar radiation, creating a horizontal thermal gradient that conducts heat toward our adjacent cable corridor. Additionally, the

road structure alters local winter snow accumulation, trapping insulating snow drifts that limit winter heat loss.

By clarifying this edge effect and integrating the Briggs et al. (2014) shading framework, we added the following in Section 4.2 (Lines 455–469): "Along this transect, the DTS cable was not buried directly beneath the gravel road embankment; rather, it was deployed along the permafrost table adjacent to the road, beneath a thinned layer of native tundra vegetation. This configuration captures a highly localized permafrost "edge effect" driven by coupled physical and ecological perturbations. Vertically, although vegetation cover persists directly over the sensor array, the canopy is thinned likely due to localized disturbances such as road dust deposition, altered hydrology, or historical construction activities. This thinned organic mat provides diminished vertical insulation and micro-shading during the summer, enabling enhanced vertical solar heat penetration down to the permafrost table, illustrating the inverse of the localized vegetation canopy-shading protection detailed by Briggs et al. (2014). Laterally, the nearby gravel embankment acts as a prominent solar heat sink, establishing a horizontal thermal gradient that conducts heat laterally toward the DTS cable transect. Additionally, the physical barrier of the road embankment alters winter wind patterns and snow-drifting dynamics, trapping thick, insulating snow accumulations that limit winter heat loss. Together, these coupled vertical-lateral micro-climatic processes drive the accelerated active layer warming and thermal degradation observed at this critical subsurface boundary".

Reference added in Line 935: "Briggs, M. A., Walvoord, M. A., McKenzie, J. M., Voss, C. I., Day-Lewis, F. D., & Lane, J. W. New permafrost is forming around shrinking Arctic lakes, but will it last?. *Geophysical Research Letters*, *41*(5), 1585-1592 (2014)."

Minor comments:

- The first sentence of the abstract is too long and complex and should be broken into two

Response: It was broken into sentences.

- L27: the more precise acronym is 'FO-DTS' to indicate sensing via fiber-optics. Distributed temperature sensing can occur via a variety of technologies including thermal infrared.

Response: Replaced all DTS with FODTS (fiber optics distributed temperature sensing).

- L31: it would be helpful to indicate what type of civil infrastructure you are referring to (ie roads, buildings, etc)

Response: Line 31 added "linear" to indicate road infrastructure.

- L36: please add a quantitative metric to support the ‘accuracy’ of simulated vs observed temperatures (ie within 0.5 deg C, or similar)

Response: Since the statement about accuracy is in the Abstract, we chose not to add quantitative metric here. Then, in Section 4.4 we added such metric in sentence “Fig. 10 shows that reconstructed temperature fields closely match observed FO-DTS measurements during periods of continuous data availability, reproducing both the timing and amplitude of seasonal temperature variations, **with average localized RMSE less than 0.4 °C**.”

- L38: why is the year 2075 relevant to state here? I am not aware that is a particular inflection point for arctic warming. If it is simply based on the timescale of the climate forecast you reference, then I suggest removing the year

Response: Line 38: Replace “2075” with “over a 50-year projection period”.

- L58: Consider adding “and microtopography” since later sections rely heavily on polygonal terrain.

Response: Added.

- L74: FO-DTS is the more precise acronym as mentioned above

Response: Replaced everywhere in the manuscript.

- L77: ‘temperature dependent backscattering of light’

Response: Replaced “temperature from the backscattering of laser light” with “temperature dependent backscattering of light”.

- L99-105: This does not feel like a complete paragraph. Combined with the one above?

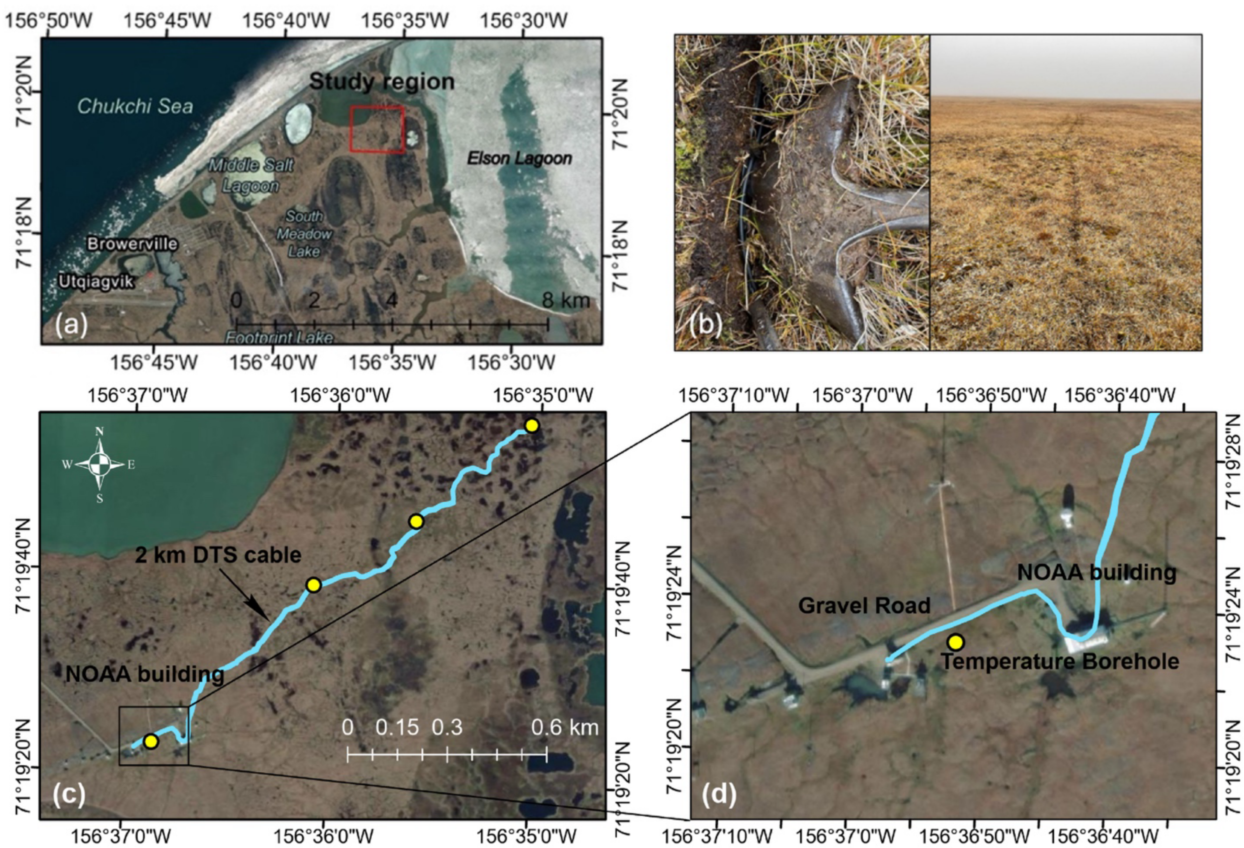
Response: The sentence was revised as: “Ground temperatures respond differently during warming and cooling phases, producing asymmetric freeze–thaw trajectories (Hu et al., 2017). The primary physical drivers of this phenomenon include thermal inertia, latent heat dynamics, and moisture-dependent heat transfer.”

- L107: please state the FODTS measurement spatial resolution, as that is at least as important as the km-scale cable length. You should also mention that the cable was buried in the soil.

Response: The sentence under Section 2 “Study area and FODTS deployment” is revised to: “A 2-km fiber-optic flat-pack multimode DTS cable **was embedded at the permafrost table** along a transect crossing civil infrastructure, undisturbed non-patterned tundra, and patterned tundra, **with spatial measurement resolution of 1 m** (Fig. 1c).”

- Why is DAS capability labeled in Fig 1 but not mentioned in the introduction? If you do not show or discuss DAS data the label should be removed from figure 1 as it is not directly relevant to this study

Response: Figure 1 is revised, and DAS label is removed. See revised Figure 1 below.



- L124: "in the Arctic coastal plain"

Response: Revised.

- L130: you could clarify why the infrastructure you monitored with FODTS might be expected to impact local soil temperatures, ie "due to altered surface energy balance and soil thermal properties"

Response: Added a sentence in Lines 154 - 156: "Specifically, these engineered structures disrupt the local surface energy balance and modify subsurface thermal properties by altering surface albedo, soil thermal conductivity, and winter snow accumulation patterns, which can be reflected by ground temperature changes".

- L131: this sentence is quite long, please break it in two

Response: The sentence was divided into two sentences in Line 160.

- L136: the air temp at time of deployment is not directly relevant to this goals of this study

Response: Sentence deleted.

- L134: fiber-optic is typically hyphenated

Response: Revised as "fiber-optic" throughout the manuscript.

- L136: 'near the base' would be better than 'close to the bottom'

Response: Revised as suggested.

- The DTS deployment section mentions multimode fiber, but DAS is labeled along with FODTS in Fig1, and I believe DAS uses single mode fiber. Please explain.

Response: The reviewer is correct. We removed reference of DAS in Figure 1.

- L159: the linear measurement spatial resolution (1 m) should be stated up front in this section. On a re-read I see it is listed in the second line, but not in a way that makes it clear to the reader the scale is 1-m, rather than referring to the meter scale more generally

Response: Line 198 Revised "meter-scale" to be "1-m".

- L186: Consider clarifying whether the model is site-specific or generalizable to other permafrost locations

Response: Added sentence in Lines 253 – 254: "The model is developed as site-specific and trained using calibrated FO-DTS data stacked as daily averages in this section".

L188: Is "Hysteresis implemented" or allowed to arise based on the physics included in the model. ie is the model deterministic

Response: The model is deterministic. The hysteresis of each channel is calculated and then applied. Revised the word "implemented" to be "calculated".

- L332: It is a stretch to say the 2-km FODTS cable surveyed "three distinct landscapes". I believe it would be more accurate to indicate that distinct patches were monitored across one permafrost landscape impacted by some basic infrastructure.

Response: Line 426 Replaced "landscapes" with "patches".

- L364: Please remind the reader what specific infrastructure you are discussing here. Is 1.4 deg C the mean difference for when you had measured data?

Response: The sentence is revised: "As revealed by Fig. 6, ground temperatures at the depth of permafrost table in the civil infrastructure area **of a road embankment** are approximately 1.4 °C higher than those in the tundra in the entire DTS data collection period, and the difference becomes more pronounced during winter (November to March of the following year), reaching a difference of 3.3 °C based on the measured data."

- L372: "these dynamics"

Response: Revised as suggested.

- L374: this sentence about fast transition in temp during thaw could use a reword, I don't follow the reasoning as stated

Response: The sentences are revised as: "Ground thawing is characterized by faster ground temperature changes, while ground freezing experiences gradual temperature changes due to the asymmetric latent heat exchanged in the water-ice phase change. The figure also clearly shows that ground temperatures in infrastructure area are consistently higher than those in the tundra throughout the recording period."

- L411: The continued referral to some minor dirt roads and a small structure as 'civil infrastructure' seems unnecessarily ambiguous for the reader. Consider just stating road/building, or whatever, more specifically. The concept of civil infrastructure brings a much more developed setting to my mind.

Response: Revised the "civil infrastructure" to "roadside".

- Section 4.4 discussion of the accuracy of simulated soil temperatures could be reinforced by RMSE, correlation, or other quantitative metrics rather than relying on qualitative language

Response: In Section 4.4 we added the RMSE: "Fig. 10 shows that reconstructed temperature fields closely match observed FO-DTS measurements during periods of continuous data availability, reproducing both the timing and amplitude of seasonal temperature variations, **with average localized RMSE less than 0.4 °C**.".

- L584: you have already defined the DTS acronym

Response: Revised to be "FODTS."

- L592-97: Please add some references to previous studies here, and do some exploration as to whether the observed warming might primarily be do to shading and moisture changes, not the infrastructure, per se

Response: We added explanation of the "localized vegetation canopy-shading protection detailed by Briggs et al. (2014)." Please refer to our responses to previous comment.