

Reviewer 1

We sincerely thank the reviewer for the time and effort dedicated to reviewing our manuscript. We are encouraged by the reviewer's positive remarks regarding the timeliness of our study and the value of our compiled dataset.

The reviewer rightly points out that our manuscript faced key challenges regarding methodological clarity, data interpretation, and statistical rigor. We agree with this diagnosis and have systematically addressed these issues. In the revised manuscript, we have implemented comprehensive improvements, including clarifying the trend analysis and sample size, revising the abstract to better reflect the role of vegetation, removing repetitive statements in the Introduction, adding recommended references, clarifying regional delineation procedures, specifying the temporal scale of ALT, reconciling inconsistent site numbers, discussing spatial resolution limitations in Section 4.4, supplementing the trend analysis with Mann-Kendall tests and sensitivity analysis, clarifying collinearity diagnostics using VIF, improving figure readability, providing robust explanations for decreasing ALT trends with multiple factors and literature support, reorganizing Section 4.3.1 to explain why GST must be considered, and expanding Section 4.4 to discuss the coarse resolution of NDVI and snow cover data as a limitation.

We believe these systematic revisions directly resolve the issues raised and will significantly enhance the scientific rigor and transparency of our study. Detailed point-by-point responses to each comment are provided in the attached supplementary document.

Question 1: Page 1: Lines 19-21: Was the statistical analysis restricted exclusively to the sampling sites exhibiting an increasing trend in ALT, or were all sampling sites across the three regions incorporated? Judging from the reported sample sizes, it appears that only the sites with upward trends were considered.

Reply: We thank the reviewer for this question. We have clarified that the trend analysis was conducted on all 219 sites with ≥ 5 years of continuous records, including both increasing and decreasing trends. The abstract has been revised accordingly, and now reads: "Based on 219 sites with more than five years of ALT records"

Question 2: Lines 24-25: Vegetation also intercepts incoming solar radiation, exerting both shading and insulating buffering effects, which helps maintain relatively cooler soil temperatures.

Reply: We thank the reviewer for this suggestion. We have revised the abstract to better reflect the role of vegetation, and the relevant sentence now reads: "Vegetation also plays a significant role in SCAP, where it intercepts incoming solar radiation, providing both shading and insulating buffering effects that modulate soil thermal regimes."

Question 3: Page 2-3: Lines 13-14, 5-6: Repetitive wording is observed between the closing lines of the first and second paragraphs on page 2. It is recommended that one instance be deleted to improve conciseness.

Reply: We thank the reviewer for this comment. We have deleted the redundant closing sentence in the first paragraph of the Introduction to improve conciseness, while keeping the second paragraph as the summary of research gaps. The revised first paragraph now ends with: "Understanding the characteristics of regional permafrost degradation is critical for reducing uncertainties in future projections and designing effective climate strategies."

Question 4: Page 3: Lines 6-7, 18-19: Similarly, the two expressions are essentially consistent in meaning. Rather than repeating this summary at the end of each paragraph, we suggest that the authors integrate it into a more appropriate position based on the specific content of the two paragraphs.

Reply: We thank the reviewer for this suggestion. We have reorganized these two paragraphs so that each focuses on different aspects without repeating the same "poorly understood" conclusion. The third paragraph now ends with: "Current understanding of the driving mechanisms behind ALT variations remains inadequate, and it remains unclear whether these mechanisms differ across diverse permafrost types. To address this gap, this study systematically analyzes ALT trends and their environmental drivers across the CAP, SCAP, and QTP permafrost regions."

Question 5: Page 4: Lines 4-6: Give the references

Reply: We thank the reviewer for this suggestion. We have added the recommended references to support the statement that current analysis of ALT data products remains insufficient. The revised text now reads: "However, current summary and deeply analysis of these data products remain insufficient (Peng et al., 2023)"

Question 6: Page 5: Line 10: ALT is the variable that the authors intend to analyze; therefore, it should not be used as a criterion for regional delineation.

Reply: We thank the reviewer for this important comment. The merging of discontinuous, sporadic, and isolated patches into SCAP was primarily due to the limited and uneven distribution of monitoring sites across these subcategories, which precluded meaningful separate analysis. We have removed the phrase "as well as the distribution of ALT sites within these zones" to clarify that regional delineation is based solely on the continuity classification of Brown et al. (1997), not on ALT values. The revised text now reads: "Based on the spatial distribution characteristics and degree of continuity across different permafrost-zone types, we merged the generic permafrost categories into three regions"

Question 7: Lines 11-14: Figure 1 appears to have been directly adopted from Obu et al. (2019). In the Methods section, the authors should further elaborate on the specific

procedures used to delineate the CAP, SCAP, and QTP regions. In particular, details regarding the overlay processing between the QTP and other permafrost classification layers should be clearly described.

Reply:

We thank the reviewer for this comment. We have elaborated on the delineation procedures in Section 2.1, clarifying that the permafrost base map is derived from Brown et al. (1997) and Obu et al. (2021). The QTP was treated as an independent region because its elevation-driven permafrost regime differs fundamentally from the latitude-driven permafrost in the Arctic and sub-Arctic. The revised text now reads: "Because the QTP was treated as an independent region primarily because it is a relatively distinct geographical unit, and its elevation-driven permafrost regime differs fundamentally from the latitude-driven permafrost in the Arctic and sub-Arctic. Any areas that fell within the QTP boundary were assigned to the QTP region, regardless of their classification in Brown et al. (1997)."

Question 8: Page 6:

Line 4: The authors should explicitly specify the temporal scale for the ALT

Reply:

We thank the reviewer for this suggestion. We have specified that all ALT records represent the annual maximum thaw depth within a given calendar year. The revised text now reads: "This study utilized site-scale, annual time series of ALT data. All ALT records represent the annual maximum thaw depth per calendar year, with measurements typically conducted in September or October."

Question 9: Line 7: The authors state on page 4 that the GTN-P database contains 305 sites, yet here is 406. This inconsistency should be reconciled.

Reply:

We thank the reviewer for catching this inconsistency. We have removed the specific number "305" from the Introduction to avoid inconsistency with the 406 sites extracted from GTN-P in the Methods section. The revised text now reads: "...the Circumpolar Active Layer Monitoring (CALM) network and the Global Terrestrial Network for Permafrost (GTN-P) have provided point-measured ALT data since the 1990s."

Question 10: Page 7:

Line 7: The abstract states "291 sites," whereas the Methods and Results sections report "219 sites." We recommend that the authors verify the correct number and ensure consistency throughout the manuscript.

Reply: We thank the reviewer for this comment. We have corrected the abstract to report 219 sites, consistent with the Methods and Results sections. The abstract now reads: "Based on 219 sites with more than five years of ALT records"

Question 11: Page 8:

Table 1: It should be noted that the marked differences in spatial resolution among the

datasets employed here may introduce substantial deviations when comparing the results with those obtained from previous site-based observational studies. In particular, the coarse resolution of climatic forcing data is likely to severely attenuate the detected contribution of climatic factors.

Reply:

We thank the reviewer for this important comment. We have added a detailed discussion in Section 4.4 acknowledging the limitations imposed by varying spatial resolutions among the environmental datasets. The revised text now reads: "Third, the environmental datasets employed in this study have varying spatial resolutions (ranging from 30 m for topography to 0.1° for climate data and 8 km for NDVI). This mismatch in spatial scales may introduce uncertainties when attributing ALT variations to specific environmental factors, particularly for climatic variables whose coarse resolution may not adequately capture local-scale temperature and precipitation gradients"

Question 12: Line 3: The trend analysis is based solely on linear regression with $p < 0.05$, but the authors have not adequately addressed issues related to variable series lengths, missing data, autocorrelation, or nonlinear temporal dynamics linear trends may lack stability. It is advisable to incorporate Mann–Kendall tests and Sen's slope estimates, and to evaluate the sensitive. Since the inclusion criterion permits sites with as few as five consecutive years of observations, the derived variety of the results to short time series, with explicit discussion of how record length may affect trend significance.

Reply:

We thank the reviewer for this valuable suggestion. We have supplemented the trend analysis with Mann-Kendall non-parametric tests and Sen's slope estimates, and added a sensitivity analysis comparing sites with ≥ 10 years versus 5-9 years of records. The following text has been added to Section 3.2: "To assess the robustness of the trends derived from linear regression, we further applied the Mann - Kendall non-parametric test and Sen's slope estimator. The Mann - Kendall results were broadly consistent with those from the linear regression. Of the 219 sites, 137 sites (62.5%) exhibited increasing ALT trends, of which 64 (29.2%) were statistically significant... To evaluate the sensitivity of our results to short time series, we compared the trend patterns between sites with longer (≥ 10 years,) and shorter (5 - 9 years,) observation records."

Question 13: Page 9: Line 6: How are data with collinearity handled?

Reply:

We thank the reviewer for this question. We have clarified in Section 2.4.3 that VIF diagnostics were used to detect collinearity; collinear variables with $VIF > 10$ were excluded, and after this exclusion all remaining variables had VIF values below the threshold. The revised text now reads: "Consistent with commonly used guidelines in statistical modelling, VIF values greater than 10 were taken to reflect severe multicollinearity in this study (Marquardt, 1970). Collinear variables with $VIF > 10$

were excluded from the final models, and after this exclusion, all remaining predictors had VIF values below the threshold. The detailed VIF results and variable selection procedures are presented in Section 3.3."

Question 14: Page 12:

Line 11-12: The comparison results are not clearly evident because the analysis for SCAP and QTP appears to have been omitted. The authors should include the corresponding analyses for these two regions. Alternatively, the authors should refer to Figure 3 in this paragraph to support the statement.

Reply:

We thank the reviewer for this suggestion. We have added a reference to Figure 3 in the paragraph comparing regional trends to ensure the comparison is clearly supported by visual evidence. The revised text now reads: "These results demonstrate that ALT increases are more common in the SCAP and QTP, indicating more widespread and pronounced permafrost degradation in these regions (Fig. 3)."

Question 15: Page 14:

Lines 15-16: Should this not be GST (Ground Surface Temperature) instead?

Reply:

We thank the reviewer for this question. GST was defined in Table 1 as Mean Growing Season Temperature. In Section 4.3.1, we explicitly refer to this definition and clarify that GST represents the mean air temperature during April – October, to avoid confusion with Ground Surface Temperature. The revised text now reads: "GST is defined as the mean air temperature during April – October (see Table 1)."

Question 16: Page 15-16:

Fig. 4: The font size and the significance asterisks in Figure 4 should be enlarged to improve readability. The term "Hot figures" should be revised to "Heatmaps" for accuracy and standard terminology.

Reply:

We thank the reviewer for this suggestion. We have regenerated Figure 4 with enlarged fonts and significance asterisks, and revised the title from "Hot figures" to "Heatmaps"

Question 17: Page 17:

Line 8: The PLS-PM approach serves as a critical method for interpreting the driving mechanisms in this study. However, the model specifications differ across the three regions (CAP, SCAP, and QTP), with varying sets of observed variables (e.g., TEMP). The authors should provide a clearer and more consistent justification for: (1) the construction of latent variables (e.g., which specific indicators constitute "soil," "temperature," "topography," "snow," etc.); (2) the criteria used for retaining or excluding particular observed variables; (3) the rationale for path directions and whether they are grounded in prior theoretical frameworks; and (4) why the model structures are not uniform across the three regions, and whether this regional

differentiation is methodologically justified or imposes limitations on cross-regional comparisons.

Reply:

We thank the reviewer for this detailed and constructive comment. We have substantially revised Section 3.5 to provide clearer justification for all four points. The revised text now reads: "The model structures were not forced to be identical across the three regions because each region required region-specific indicator specifications to achieve acceptable model quality. All final models satisfied the standard PLS-SEM evaluation criteria: composite reliability (CR) exceeded 0.70, average variance extracted (AVE) exceeded 0.50, HTMT values were below 0.90. These criteria were used iteratively to refine each regional model: indicators that led to low loadings, insufficient CR/AVE, or HTMT violations were removed or replaced until all quality thresholds were met. Consequently, the final indicator sets differ across regions because each dataset exhibited distinct measurement characteristic. The path directions in the structural model were specified following established permafrost theory (Jorgenson et al., 2010; Wang et al., 2022)."

Question 18: Page 18:

Lines 19-20: The supplementary materials referred to in the manuscript could not be found.

Reply:

We thank the reviewer for this comment. The supplementary materials are now included and properly referenced in the manuscript. Additionally, we have combined the point-by-point responses and the supplementary materials into a single compressed file for convenient upload and review.

Question 19: Page 19:

Fig.6: The readability of the figures needs improvement: the font size is too small, and the line colors should be darkened for better contrast.

Reply:

We thank the reviewer for this suggestion. We have regenerated Figure 6 with larger fonts and darker lines for improved readability.

Question 20: Page 20:

Lines 6-8: The current reasoning appears tenuous and requires either stronger empirical evidence or a more cautious interpretation.

Reply:

We thank the reviewer for this comment. We have substantially revised this paragraph to provide a more robust and evidence-based explanation for decreasing ALT trends. Instead of attributing this pattern solely to insufficient warming, we now consider multiple factors. The revised text now reads: "The decreasing trends observed at the remaining 40% of sites do not necessarily contradict this overall pattern. Several factors may contribute to this local variability. First, although high-latitude regions have experienced pronounced warming (Peng et al., 2023), absolute temperatures in

some areas may still remain below the thresholds required to trigger significant permafrost thaw. Second, local environmental conditions—such as vegetation cover, snow dynamics, and soil thermal properties—can buffer the warming signal and delay ALT deepening (Jorgenson et al., 2010; Smith et al., 2022). Third, interannual climate variability may modulate the warming trend, leading to temporary decreases in ALT at some sites (Groenke et al., 2024). Fourth, in ice-rich permafrost regions, thaw of excess ground ice can cause thaw settlement (surface subsidence), which lowers the ground surface while the thaw front also descends, resulting in stable or even decreasing ALT records despite ongoing permafrost degradation (Shiklomanov et al., 2013; Luo et al., 2023)."

Question 21: Line 10: The use of the word "supports" in this context is not accurate / is imprecise.

Reply:

We thank the reviewer for this comment. We have replaced the word "supports" with more neutral and accurate wording throughout the discussion. The relevant sentence has been revised accordingly.

Question 22: Page 20:

Lines 21-23: Give the references

Reply:

We thank the reviewer for this suggestion. We have added the reference to Groenke et al. (2024) to support the statement regarding limited influence of temperature fluctuations on soil heat transfer. The revised text now reads: "...and such variations exert only limited influence on soil heat transfer (Groenke et al., 2024)."

Question 23: Page 22: Line 7: air temperature or soil temperature?

Reply:

We thank the reviewer for this question. We have defined GST as the mean air temperature during April – October to clarify that it is an atmospheric temperature indicator, not Ground Surface Temperature. The revised text now reads: "GST is defined as the mean air temperature during April – October (see Table 1)."

Question 24: Lines 21-24: This sentence should be rephrased, as the current wording is imprecise and lacks sufficient evidentiary support.

Reply: We thank the reviewer for this comment. We have substantially reorganized Section 4.3.1 to clearly explain why GST must be considered. We have removed the imprecise statement regarding "transient pulse-like effects" and replaced it with a clearer comparison between MAT and GST, supported by appropriate literature. The revised text now reads: "When analyzing the effects of air temperature on ALT, both MAT and GST must be considered. GST is defined as the mean air temperature during April – October (see Table 1). Although MAT has been widely identified as a primary driver of ALT increase (Peng et al., 2023; Yang et al., 2024), it includes winter temperatures that have little direct effect on seasonal thaw depth. In contrast, GST

directly captures the cumulative thermal forcing available for ground thaw during the active thawing season (Brown et al., 2000; Dobinski, 2011). Previous studies have also highlighted the close coupling between air temperature and soil temperature at various depths (Brown et al., 2000; Dobinski, 2011; Yang et al., 2024)."

Question 25: Lines 17-24: The current text does not clearly explain why GST must be taken into account. We suggest that the authors rephrase/reorganize this section to improve clarity and logical flow.

Reply:

We thank the reviewer for this suggestion. We have substantially reorganized Section 4.3.1 to clearly explain why GST must be considered: unlike MAT, which includes winter temperatures with limited effect on thaw depth, GST directly captures the cumulative thermal forcing during the active thawing season. We have removed the imprecise "transient pulse-like effect" statement and replaced it with a clearer comparison between MAT and GST, supported by appropriate literature. The revised text now reads: "When analyzing the effects of air temperature on ALT, both MAT and GST must be considered... Although MAT has been widely identified as a primary driver of ALT increase (Peng et al., 2023; Yang et al., 2024), it includes winter temperatures that have little direct effect on seasonal thaw depth. In contrast, GST directly captures the cumulative thermal forcing available for ground thaw during the active thawing season (Brown et al., 2000; Dobinski, 2011)."

Question 26: Page 24:

Lines 1 and 16: In the CAP and SCAP regions, vegetation and snow cover are recognized as important indicators influencing permafrost dynamics. However, the current results show that neither factor has a statistically significant effect. This may be largely attributable to the coarse resolution of the datasets used, rather than reflecting actual field conditions—especially given that the analysis is not based on site-specific monitoring data. The authors should provide a thorough discussion of this limitation in the Discussion section.

Reply:

We thank the reviewer for this important suggestion. We have expanded Section 4.4 to explicitly discuss the coarse resolution of NDVI (8 km) and snow cover data (0.1 °) as a limitation, acknowledging that this may partly explain why vegetation and snow cover showed limited or non-significant effects on ALT in our PLS-PM results. The revised text now reads: "This limitation may partly explain why vegetation and snow cover showed limited or non-significant effects on ALT in our PLS-PM results (Sections 4.3.3 and 4.3.4), as the coarse-resolution NDVI (8 km) and snow cover data (0.1 °) may not capture fine-scale heterogeneity at individual monitoring sites. Site-specific measurements of vegetation and snow characteristics would be necessary to more accurately quantify their roles in ALT dynamics."

We sincerely thank the reviewer again for the thorough and constructive review. We believe the revised manuscript has been substantially improved and hope it now meets

the standards for publication.