Response to Reviewer #3

Dear Editor and Reviewer,

We are grateful to Reviewer #3 for their insightful and constructive comments, which have been instrumental in enhancing the scientific rigor and clarity of our work. We have addressed all comments in detail, and our responses are outlined below.

Major Comments

Comment R3-1: **Innovation and effectiveness of the DEM-based correction method appear overstated**

"The correction relies solely on a 1-D lapse-rate relationship and ignores slope, aspect, surface properties, and land-cover influence—despite the study area being described as a "mountainous region with complex topography." Such a simplification is unlikely to adequately capture spatial temperature variability in the SAYR(Liang et al. 2014). The justification of "data limitations" is insufficient, and the authors should explicitly discuss the uncertainty introduced by ignoring other factors."

Response:
We thank the reviewer for raising this important methodological point. The concern is fully valid, and we have revised Section 2.3 and the Discussion to clarify both (i) the rationale for adopting a 1-D elevation-based correction, and (ii) the uncertainties caused by not explicitly incorporating slope, aspect, and land-cover effects.

(1) Scientific rationale for a 1-D lapse-rate correction

Our intention is not to overstate methodological novelty. The DEM-based correction here is positioned as a **physically explicit and transparent elevation correction**, not a complete downscaling framework. We now clearly state that:

- This method follows widely used elevation-based correction approaches in cold-region and mountain-climate studies (e.g., temperature–elevation regression).
- Elevation exerts the dominant first-order control on surface temperature over the Tibetan Plateau, especially at monthly timescales relevant to freeze–thaw indices.
- Slope/aspect corrections require long-term high-frequency radiation or surface-energy-balance observations, which are not available in the SAYR.

(2) Explicit discussion of uncertainties introduced by ignoring slope/aspect

As suggested, we now explicitly discuss the limitations:

- South-facing slopes and highly vegetated areas may experience stronger radiative warming not captured by the purely elevation-based model.

- North-facing shaded terrain may retain cold biases.
- Sparse station distribution (7 sites concentrated along transportation corridors) limits the ability to calibrate spatial heterogeneity beyond elevation.

(3) Added text to Discussion

To strengthen transparency, we expanded the Discussion to note that even after DEM correction. The revised text now explicitly acknowledges that:

(i) coarse-scale terrain representation in the original 0.1° ERA5-Land field cannot be fully corrected in regions with highly complex topography; and

(ii) the lapse-rate correction uses a one-dimensional elevation–temperature relationship, without explicitly incorporating slope, aspect, land-cover heterogeneity, or surface radiative contrasts.

These omitted factors may introduce localized residual biases (e.g., on south-facing slopes or shaded valleys), and the sparse station network further constrains the correction accuracy. This clarification clearly delineates the applicability and limitations of the corrected dataset.

Modification in manuscript:
Section 2.3 now states that the lapse-rate correction captures the dominant elevation signal but does not explicitly incorporate slope, aspect, or surface radiative properties due to data limitations.

(Section 2.3 Lines 122 – 131)

Section 5 includes a strengthened paragraph describing where residual uncertainties may occur and how future multi-source fusion or energy-balance modeling can improve fine-scale accuracy.

(Section 2.3 Lines 412 – 418.)

Comment R3-2: ***Only seven meteorological stations are used, which is inadequate***

Reviewer comment:
Using 7 stations only to represent a region greater than 40,000 km² is extremely sparse. Moreover, most stations are located in low-elevation accessible areas, likely causing substantial biases in lapse-rate estimation. Therefore, I recommend providing cross-validation or leave-one-out tests, examining spatial/temporal stability of lapse rates, and considering using auxiliary datasets (e.g., MODIS LST).

Response:

We thank the reviewer for highlighting the limitations associated with the sparse meteorological network. We fully agree that seven stations distributed unevenly across a large and topographically complex region introduce uncertainty into lapse-rate estimation. In response, we have strengthened both the analysis and the discussion of uncertainty as follows:

First, lapse-rate estimation in our study is based on the full 1981–2020 monthly mean climatology from all available CMA stations, which provides a long-term and physically representative elevation–temperature relationship rather than a statistical training model requiring calibration/validation partitioning. This climatological fitting approach follows previous applications in data-sparse cryospheric regions.

Second, to ensure independent evaluation, we conducted a temporal validation using monthly STobs from 1981–2015, which were not used in lapse-rate estimation. This provides an independent assessment of the DEM-corrected ERA5-Land ST across the multi-decadal period. The revised Figure 4 now explicitly distinguishes the lapse-rate fitting dataset (1981–2020 monthly means) from the validation dataset (1981–2015 monthly STobs).

Third, we acknowledge that the sparse station network may introduce elevation-biased uncertainties, particularly at very high elevations. This limitation has been explicitly added to the Discussion, and we now state that future work should incorporate additional datasets (e.g., MODIS LST, in situ permafrost observations, high-resolution reanalysis) to improve spatial representativeness.

We believe these revisions clarify both the robustness and the limitations of the current approach.

Modification in manuscript:
Clarifications were added in Sections 3.1.2.

(Section 3.1.2 Lines 244 – 248.)

Comment R3-3: ***The performance of the corrected skin temperature requires more critical assessment***

Reviewer comment:
In Fig. 4, although the R^2 value is high, the axes are plotted over different ranges, making the agreement appear stronger than it is. A 1:1 reference line should be added. Visual inspection suggests large deviations between corrected ST and station observations. Moreover, the RMSE value (1.22 °C) appears inconsistent with the scatter distribution and should be recalculated.

Response:

Thank you for this important comment. We have fully revised Figure 4 to provide a more transparent and rigorous evaluation. The revised figure now includes （Figure R1）：

(1) identical axis ranges for observed and corrected temperatures;
(2) a 1:1 reference line;
(3) separate panels for lapse-rate fitting (1981–2020 climatology) and independent temporal validation (1981–2015 monthly STobs); and
(4) recalculated performance statistics (R^2, RMSE, ubRMSE) based strictly on the validation dataset.

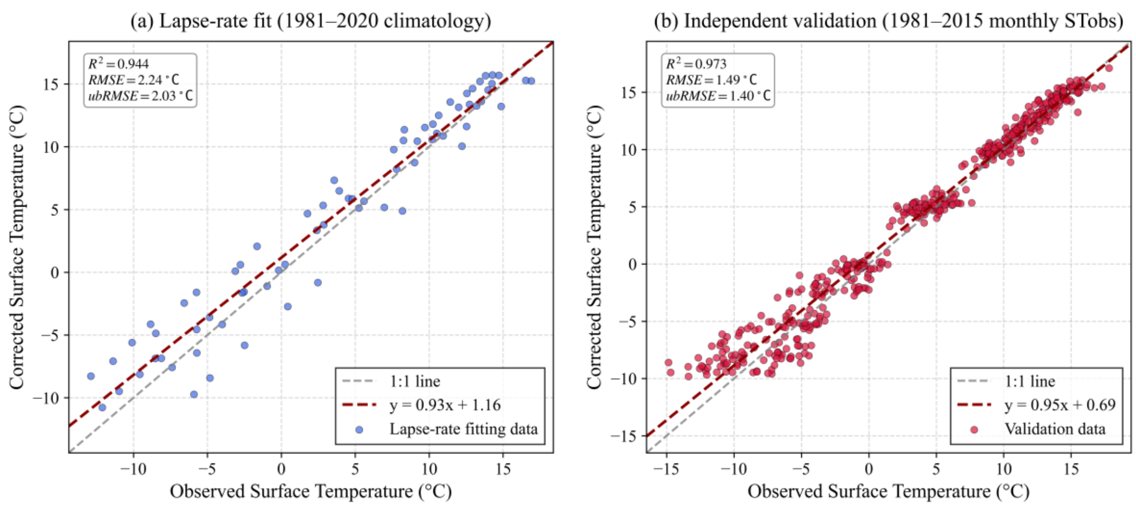

Figure R1 Validation of the DEM-corrected ERA5-Land surface temperature (ST) against CMA station observations (STobs). (a) Lapse-rate fitting dataset (monthly climatology, 1981–2020).(b) Independent temporal validation dataset (monthly time series, 1981–2015). The 1:1 reference line is shown for comparison. Performance statistics (R^2, RMSE, ubRMSE) are reported in each panel.

Modification in manuscript:

– Figure 4 replaced with a two-panel version showing (a) lapse-rate fitting and (b) independent validation, including 1:1 lines and unified axis limits.
– Section 3.1.2 revised to report the updated RMSE and ubRMSE values computed solely from the independent validation dataset.

(Section 3.1.2 Lines 212– 230.)

Comment R3-4 : ***FI/TI derived from monthly mean temperatures produce large uncertainties***

Reviewer comment:

Freezing and thawing indices are conventionally calculated from daily temperature sums(Peng et al. 2019). Using monthly mean temperatures can introduce very large errors—especially during transition seasons when daily temperatures oscillate around 0°C. The manuscript should quantify this uncertainty or justify the applicability of *monthly data for FI/TI estimation in this region(Liu et al. 2021).*

Response:

We thank the reviewer for this important comment. Following the suggestion, we performed a full uncertainty assessment using all available station-observed daily surface temperature (STobs) records (1981–2020). Daily FI/TI were computed using the traditional degree-day summation approach, and were compared against FI/TI derived from monthly mean temperatures at the same stations. The results show that monthly TI/FI reproduces daily TI/FI with high consistency:

(1) Overall agreement（Figure R2、R3）

- TI: Mean $R^2 = 0.97$ across stations
- FI: Mean $R^2 = 0.98$

(2) Mean uncertainty (Monthly − Daily)

- TI bias: 12–15 °C·day (station mean)
- FI bias: -21 –-15°C·day

(3) RMSE

- TI RMSE: 19.85–26.60 °C·day
- FI RMSE: 24.99–28.61 °C·day
  Errors mainly occur in transition months.

(4) Seasonal behavior

- Summer: Errors negligible (RMSE < 3 °C·day)
- Winter: Moderate but stable (RMSE 2–8 °C·day)
- Transition seasons (Mar–Apr & Oct–Nov):
  RMSE peaks (16–46 °C·day), consistent with reviewer's expectation because daily temperatures cross 0 °C frequently.

Importantly, despite the transitional-season deviations, annual TI and its interannual variability were nearly identical between daily- and monthly-derived estimates. Therefore, for climate-scale analyses over four decades, monthly mean temperatures provide sufficiently robust FI/TI estimates in the SAYR.

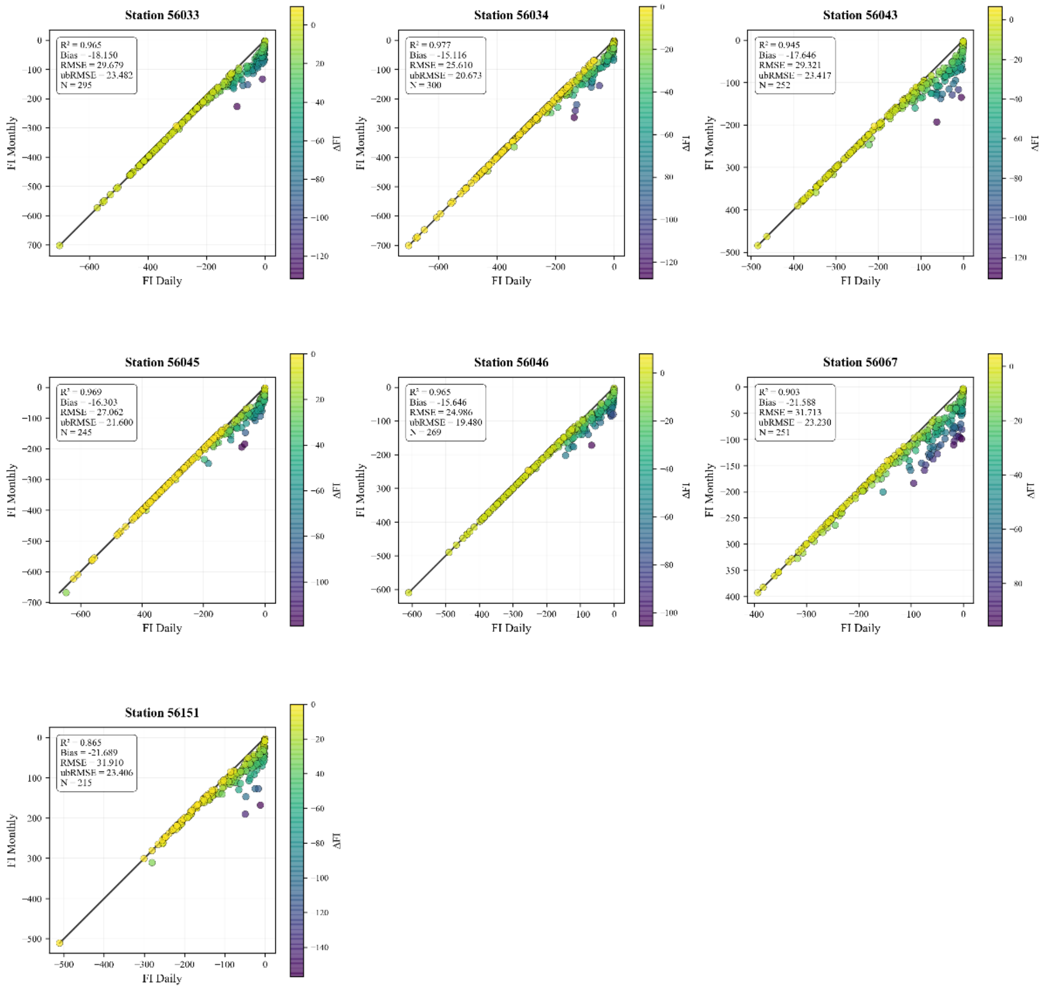

Figure R2 Comparison of FI derived from monthly vs daily temperature (all stations combined).

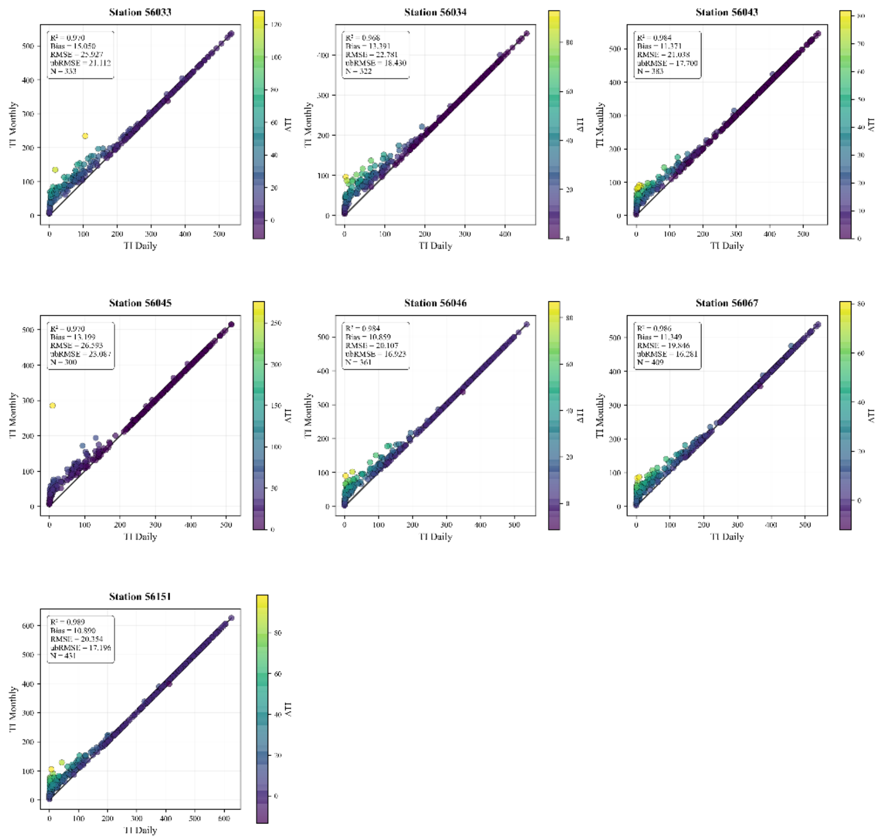

Figure R3 Comparison of TI derived from monthly vs daily temperature (all stations combined).

Modification in manuscript:

We have incorporated these findings into Section 4.1 and added a supplementary figure and table.

(Section 4.1, Lines 428– 434.)

Comment R3-5: ***Snow cover effects are not discussed***

Snow strongly insulates the soil, and snow-surface temperature (represented by ERA5-Land SKT) often differs substantially from soil-surface temperature below the snowpack(Peng et al. 2024). This may significantly bias winter SFI, STI, and N-factor values. A discussion of how snow processes affect the results is necessary.

Response:

We appreciate the reviewer's important observation. Snowpack indeed modifies the ground–atmosphere thermal coupling by reducing conductive heat loss and decoupling snow-surface temperature (SKT) from the soil surface. We have now included a dedicated discussion acknowledging that ERA5-Land SKT tends to be colder than the physical ground surface under deep or persistent snow, which may introduce winter biases in SFI, STI, and N-factor estimates. We clarify that this limitation mainly affects absolute winter magnitudes rather than interannual variability or spatial patterns. The revised text also outlines that future work will incorporate snow-depth and snow-insulation parameters (e.g., from ERA5-Land, MODIS) to reduce these uncertainties.

Modification:

These revisions are now included in the manuscript (*Section 4.1, Lines 437–442*).

Comment R3-6: ***Novelty is limited***

FI/TI patterns in global permafrost zones, even in Qinghai-Tibet Plateau have been widely reported ,e.g., (Qin et al. 2021) (Fang et al. 2023). The authors should better articulate what new scientific insights are provided beyond producing a regional dataset.

Response:
We thank the reviewer for this important comment. We agree that FI/TI analyses have been widely performed at continental and plateau scales. In response, we have revised the Introduction and Conclusion to clarify the specific contributions of this study and to avoid overstating novelty. Our work does not claim methodological innovation beyond established lapse-rate correction approaches. Rather, its contribution is **regional and application-oriented**:

1. **We produce the first 1-km, 40-year (1981–2020) surface-temperature dataset specifically for the Source Area of the Yellow River (SAYR)**—a region where no comparable long-term, high-resolution product previously existed. Existing QTP-wide products (e.g., Qin et al. 2021; Fang et al. 2023) typically provide 5–10 km resolution or shorter time coverage, which cannot resolve the steep terrain gradients and local freeze–thaw heterogeneity in the SAYR.
2. **This dataset enables a spatially explicit assessment of freeze–thaw dynamics**, including elevation-banded FT gradients, warm-season thaw dominance, and long-term TI/SFI/STI trajectories, which were previously not characterizable using coarse-resolution data.
3. **We evaluate uncertainties of DEM correction, monthly FI/TI estimation,** which provides transparency that is often lacking in regional FT studies.

The manuscript has been revised to clearly position the contribution as a **region-specific dataset and its associated freeze–thaw assessment**, rather than a methodological breakthrough. We appreciate the reviewer's guidance and have adjusted our claims accordingly.

Modification in Manuscript:
Revised text added to the final two paragraphs of the Introduction, clarifying contribution

and avoiding overstated novelty.

Section 1, Lines 44–55.

Specific Comments:

Below is a list of language, formatting, and consistency issues identified in the manuscript:

1. ***Line 57:*** *Incorrect reference formatting.*

   Response:
   Thank you for pointing that out. I have reviewed and revised each citation individually according to the journal's formatting requirements.

2. ***Lines 66–70:*** *The sentence on NDVI and ecological risks monitoring is unclear and should be rewritten.*

   Response:
   The sentence describing NDVI and ecological risk monitoring has been rewritten for clarity.
   Original unclear sentence replaced by:
   "Previous studies have shown that vegetation NDVI exhibited an overall increasing trend from 2000 to 2019; however, the ecological risks caused by permafrost degradation, climate warming, and atmospheric humidification still require long-term monitoring (Cao et al., 2021)."

3. ***Line 75:*** *"Datas" →* ***"Data"*** *or* ***"Datasets"****.*

   Response:
   "Datas" has been corrected to "Datasets."

4. **Figure 1:** *The legend states "red triangles," but the figure shows* ***red circles****.*

   Response:
   Thank you for your feedback. The legends and graphic symbols have been standardized.

5. **Lines 77–78:** *Provide data source citation.*

   Response:
   Thank you for pointing that out. The data source citation has been added.

6. **Line 119:** *Clarify the meaning of "each month t."*

   Response:

Thank you for pointing that out. The meaning of "each month t" has been clarified as referring to each calendar month (January–December).

7. **Line 126:** *"°C/100m-1" should be* ***"°C/100 m"*** *or* ***"°C 100 m^{-1}"***.

   Response:
   Thank you for pointing that out. The notation has been corrected to "°C/ 100 m.

8. **Line 178:** *"Figure S3" should be* ***"Figure S2."***

   Response:
   Thank you for pointing that out. The figure reference has been corrected to Figure S2.

9. **Line 195:** "person's correlation coefficient" → **"Pearson's correlation coefficient."**

   Response:
   Thank you for pointing that out. Corrected to "Pearson's correlation coefficient."

10. **Lines 200–202:** *The meaning of the sentence is unclear.*

    Response:
    We thank the reviewer for noting the clarity issue. The sentence has been rewritten to explicitly identify the months representing the strongest and weakest lapse rates and to clearly report their corresponding values.
    Revised text:
    "Analysis of the monthly lapse rates shows that the strongest temperature–elevation gradient occurs in winter (December: −0.85 °C 100 m^{-1}; $R^2 = 0.952$), whereas the weakest gradient is observed in summer (July: −0.43 °C 100 m^{-1}; $R^2 = 0.852$)."

11. **Figure 3 and Table S1** *are redundant—consider removing one.*

    Response:
    We agree that Figure 3 already conveys the full information visually.
    Table S1 has been removed to avoid redundancy, and the figure is retained as the primary representation of the monthly lapse-rate statistics.

12. **Lines202–206 and239–242:** *belong to discussion.*

    Response:
    We agree that these sentences constitute physical interpretation and belong to the Discussion section.
    The corresponding paragraphs have been moved to Sections 4.1 and 4.3, respectively, and slightly revised for clarity.

13. **Figure 5:** *The y-axis label is unclear.*

    Response:
    Thank you for pointing that out. The y-axis label has been revised for clarity.

14. **Line 253:** *"900.01°C" should be* ***"900.01 °C·day."***

    Response:
    Thank you for pointing that out. The unit and value labels have been corrected.

15. **Figures 6–8:** *Colorbar ranges should be consistent across subplots for comparability.*

    Response:
    We appreciate the reviewer's suggestion to standardize colorbar ranges across subplots. For Figure 6 (Na and Ng), we have unified the colorbar limits to improve direct comparability. However, for Figures 7–8, the freezing index (FI) and thawing index (TI) differ substantially in magnitude and dynamic range. Applying a single shared color scale would compress the spatial gradients and obscure meaningful patterns, especially in high-elevation zones. To preserve the readability and interpretability of each variable, we retained variable-specific colorbar ranges.

16. **Line 300:** *What does "FFI" mean??? Please correct it.*

    Response:
    Thank you for pointing that out. "FFI" has been corrected to "FI."

17. **Line 324:** *"thawning" →* ***"thawing."***

    Response:
    Thank you for pointing that out. "thawning" has been corrected to "thawing."

18. **Lines 400–405*:*** *Meaning of the paragraph is unclear and should be rephrased.*

    Response:
    Thank you for pointing that out. This paragraph has been rewritten to clarify the logic and ensure coherence with the surrounding text.

19. **Line 407:** What do you mean by "The TI in the SAYR is found to be

considerably higher than the TI"??? Variable confusion.

Response:
Thank you for pointing that out. The sentence has been revised: "The ATI/STI in the SAYR is found to be considerably higher than the AFI/SFI……"

20. **Line 472:** "temperature increased from 85°C to 100°C" – clearly incorrect, please check it.

    Response:
    Thank you for pointing that out. The incorrect values have been corrected to the proper °C·day units."

21. *Full names of abbreviations should appear* ***only at first occurrence****, not repeatedly.*

    Response:
    Thank you for pointing that out. The text has been adjusted according to journal requirements. The full name is provided with the abbreviation in parentheses at its first appearance throughout the manuscript, with the abbreviation used in subsequent references.

22. *FI values should be expressed as negative values unless explicitly defined otherwise.*

    Response:
    Thank you for pointing that out. The FI symbol conventions have been standardized and explicitly documented within the methods.

23. *Many typing errors in "****References****" session, please check them carefully.*

    Response:
    Thank you for pointing that out. All reference entries have been carefully checked and corrected.

Summary

We sincerely thank the reviewer for the insightful comments. All suggestions have been carefully addressed, resulting in substantial improvements to the manuscript's clarity, rigor, and scientific contribution.

Sincerely,
Hongying Li, on behalf of all co-authors.