# Author's Responses to RC2's comments on *"Brief communication: Reanalyses underperform in cold regions, raising concerns for climate services and research"*


Bin Cao[1], Stephan Gruber [2]

[1]State Key Laboratory of Tibetan Plateau Earth System Environment and Resources (TPESER), National Tibetan Plateau Data Center (TPDC), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China
[2]Department of Geography & Environmental Studies, Carleton University, Ottawa, ON, Canada

**Correspondence**: Bin Cao (bin.cao@itpcas.ac.cn)


The authors would like to thank the reviewer for their constructive feedback and thorough assessment of our manuscript. Below, we provide a point-by-point response to each comment, reviewer comments are given in black, responses are given in blue. Additionally, we have included details of how we intend to address these changes in a potential revised submission. Revised figure/table are presented at the end of our responses.

This study by Cao and Gruber provides a timely evaluation of reanalysis performance in cold regions, underscoring key challenges in modeling mean annual air temperature (MAAT) and snow water equivalent (SWE). Presenting the work as a Brief Communication is appropriate, as it efficiently draws attention to issues of broad relevance. While a full uncertainty attribution is beyond the current scope–as noted in the response to Reviewer #1–the study lays a solid foundation for future work and enables rapid dissemination of important insights.

**Recommendation:** Minor revisions are recommended to improve clarity and strengthen the manuscript's impact. The core message is clear and timely; addressing the points below–primarily through brief clarifications or additions–would enhance the study's novelty and broader applicability without requiring new analyses.

**Additional Insights for Consideration**

**1. Clarify the role of ERA5-ENS:** The use of the ERA5 ensemble is a valuable aspect of the study. However, the distinction between uncertainty within a single system (ERA5-ENS) and the broader inter-reanalysis spread could be further emphasized. This contrast may offer readers a clearer sense of where structural versus internal uncertainties dominate.

The notably smaller spread in ERA5-ENS (yellow line, Fig. 1) compared to the full multi-reanalysis ensemble warrants explicit discussion. This comparison could provide valuable insights into the relative importance of different uncertainty sources.
Response:
**In Methods, Sec. 2.1**, this part will be revised as below to clarify: *"The 10-member ensemble of ERA5, which quantifies uncertainties in the ERA5 assimilation and modeling system, was also included here for comparison. The ERA5 ensemble provides an opportunity to show how parameter uncertainty in one reanalysis system compares with the spread between structurally different reanalyses."*

**In Results, Sec. 3.1**, we will add below part to clarify. *"Compared to the spread of multiple reanalyses that also differ in structure, the spread of the ERA5 ensemble, within a consistent assimilation system and representing mostly parametric uncertainty, is notably smaller, as excepted, i.e., 0.1 °C (0.0–0.3) for $MAAT_s$ and 1.0% (0–2.6) for relative $maxSWE_s$."*

**2. Highlight the spatial dimension of spread:** The spatial maps in Figure 2 could be enhanced by including a difference panel or masking approach (e.g., isolating highcryosphere, low-station-density zones). This could help illustrate where the reanalysis disagreement is most consequential for downstream applications.

Could the authors clarify whether the larger spread in high-altitude regions (e.g., High Asia, Greenland Ice Sheet) is primarily tied to low observation density or elevation-dependent processes (e.g., snow physics)? For instance, does Greenland's spread pattern align more with other high-altitude regions (suggesting elevation-driven uncertainty) or with low-altitude cold regions like Arctic tundra (suggesting temperature-driven uncertainty)? A brief discussion of how these factors interact in different cryospheric regimes would strengthen the interpretation of Figure 2.

**4. Elevation Dependencies:** The Tibetan Plateau case (mentioned in the text) demonstrates notable elevation-dependent warming (Gao et al., 2018). Does MAAT spread show similar elevation dependence? Such analysis could help distinguish between:
a) Station-density effects (where lower elevations typically have better observational coverage)
b) Model physics limitations (e.g., inadequate representation of elevation-specific processes like katabatic winds or radiation biases)
Response: These are the responses to the Additional Insights for Consideration 2 & 4.

In the Introduction, we intended to clarify that the Arctic amplification warming and elevation-dependent warming remain controversial depending on the datasets used, rather than demonstrating unambiguously that elevation-dependent warming occurs uniformly.

We agree the spatial and elevation-dependent analyses can provide additional insights. However, the coarse spatial resolution of reanalysis leads to inadequate representation of elevation-specific processes like precipitation, katabatic winds, or radiation in the numerical weather prediction models used.

Instead, we intend to use terrain ruggedness in the revision to distinguish the added uncertainties due to complex terrain. The roughness was estimated following Gruber (2012), and is a proxy for the potential uncertainties arising from scale effects related to the coarse reanalysis grid.

In Sec. 3, we will add: *"Figure S3 shows how ensemble spread increases with terrain ruggedness. On the other hand, the spread on the two continental ice sheets is also high even though the terrain is flat. This is likely because of inadequate representation of processes involving ice, snow, and firn."*

In the supporting information, we will add the method for roughness estimation.

***Text S1. Terrain Ruggedness***
*The terrain ruggedness (rug, m km$^{-1}$) is derived largely following Gruber 2012.*

$$rug = \frac{E_{std}}{\sqrt{A}} \tag{1}$$

*where $E_{std}$ (m) and A (km$^{-2}$) is the elevation standard and area for a analysis grid of 0.25°. The elevation is from GTOPO30 with a spatial resolution of 30 arc-second or ∼1 km.*

**3. Cryospheric Regime Variability:** The study treats cold regions (MAAT $<$ 0°C), yet these areas encompass diverse cryospheric regimes (e.g., high-altitude glaciers versus Arctic tundra). To enhance the analysis, the authors might consider: Stratifying results by cryosphere type: Does MAAT spread differ significantly between permafrost-dominated versus snow-dominated regions? For instance, snow-physics errors (such as MERRA-2's precipitation correction limitations) may be predominant in mountainous areas, while soil-thermal biases (Cao et al., 2020) might dominate in permafrost zones. A supplementary map or table categorizing spread according to cryosphere classification (using the already collected PZI and snow cover data) could reveal important process-specific discrepancies.

Response: In the revision, the spread will be aggregated for each specific cryosphere element, including: ice sheets and glaciers, snow cover, permafrost, and seasonally frozen ground, following Figure 2A. To achieve this, we will add a new table (Table 1) with spread for each specific element. On the other hand, we will move the original Table 1 of reanalysis information to supporting information (as Table S1) in order to avoid excessive length in the manuscript. These four elements may have some overlap in spatial due the corse spatial resolution of reanalysis and inherent features of the cryosphere. For these reasons, the classification is carefully treated. In sec. 2.5 Cryosphere occurrence of the revision, we will clarify as below.

*"To distinguish the variability between cryospheric regimes, the spread was individually analyzed for each cryosphere element. Ice sheets-dominated areas include the Greenland and Antarctic ice sheets; areas with more than 30 snow-covered days were considered snow-dominated; areas with PZI $\geq$ 0.1 were considered permafrost-dominated area; and areas with frozen soil $\geq$ 30 days (excluding permafrost-dominated areas) were considered seasonally-frozen-ground-dominated areas."*

In Sec. 3.1, we will add a brief clarification for specific cryopshere element variability. *" While the overall spread is remarkable in cold regions, the ice sheet areas show most significant spread, which is about 2.3 times greater for MAAT and 1.7 times greater for maxSWE compared to that in seasonally-frozen-ground-dominated areas based on all five reanalyses (Table 1, Fig. 1)."*

**5. Temporal Analysis of Spread:** Given that Arctic amplification rates have shown distinct shifts approximately between 1990-2005 and 2015-2020 (Rantanen et al., 2022), it would be valuable to examine whether ensemble spread has corre-

Table 1: The spread of mean annual air temperature ($MAAT_s$, °C) and relative maximum snow water equivalent ($maxSWE_s$, %) for the areas occupied by specific cryosphere elements.

| Cryosphere element | $MAAT_s^{all}$ | $MAAT_s^{4DV}$ | $SWE_s^{all}$ | $SWE_s^{4DV}$ |
|---|---|---|---|---|
| Ice sheets & glaciers | 2.27 (1.05–3.58) | 2.03 (0.62–3.79) | 197.3 (171.6–206.6) | 154.0 (92.7–190.2) |
| Snow cover | 0.77 (0.28–1.39) | 0.52 (0.10–1.15) | 79.9 (52.9–115.0) | 72.3 (49.6–104.5) |
| Permafrost | 0.97 (0.47–1.65) | 0.80 (0.24–1.49) | 74.6 (50.4–108.4) | 82.7 (53.7-123.1) |
| Seasonally frozen ground | 0.68 (0.24–1.29) | 0.37 (0.08–0.78) | 72.0 (49.1–105.9) | 78.7 (52.4–108.4) |

Values are reported as mean (10th to 90th percentile).
Superscripts distinguish all five (all) reanalyses and the three 4DVar modern reanalyses (4DV), only.

spondingly decreased in more recent years (particularly post-2000 with improved satellite assimilation). A persistent spread despite improved observations would strongly indicate fundamental process-representation issues beyond observational limitations.
Regarding to the temporal changes of spread, we will extend the analysis back to the earliest period for which data is available. We will add a brief description (Sec. 3.1) and two sub-figure in Figure 2 (E and F).

In Results Sec. 3.1, we will add *"The temporal analyses revealed that the spread in MAAT and maxSWE was generally reduced since 1980, with the increased assimilation of satellite datasets (Fig. 2E and F, Hersbach et al., 2019). For example, the $MAAT_s$ in 2010s was reduced by 0.23 °C compared to that in 1960s for the 4DVar reanalyses. But a persistent spread found since 1980 despite improved observations may indicate process-representation issues in the numerical weather prediction models."*

**Suggested Improvements:**
1. The inclusion of a simple elevation-binned analysis (using existing data) could significantly strengthen the interpretation of regional variations in spread.
Response: Please see our responses to the Additional Insights for Consideration 4 Elevation Dependencies.

2. A brief discussion of how cryosphere type and elevation might interact to produce the observed spread patterns would enhance the manuscript's conceptual framework.
Response: Please see our responses to the Additional Insights for Consideration 3 and 4.

3. The temporal analysis of spread could be incorporated without requiring substantial new analysis, as the study already covers 1991-2020.
Response: Please see our responses to the Additional Insights for Consideration 5 Temporal Analysis of Spread.

**Specific Comments:**

L36: Could the authors clarify what defines the 1991–2020 period as 'high quality' for reanalyses? For example, does this refer to improved satellite data assimilation, expanded observational networks, or advances in modeling? A brief explanation would help contextualize the results." Also, what do the authors mean by high quality observation in L56?
Response: We will revise as below to clarify

*"The three most recent decades 1991–2020, which had improved satellite observation and data assimilation, were used."*

Lines 97-100: "Qin et al. (2020); Kraaijenbrink et al. (2021)." >> (Qian et al., 2020; Kraaijenbrink et al., 2021) "Cao et al. (2020); Domine et al. (2019)" >> (Cao et al., 2020; Domine et al., 2019) "Reichle et al. (2017)" >> (Reichle et al., 2017)
Response: Will be revised.

L159:(CDS), C.C.C.S.C.C.D.S? Could the authors update it to follow the recommended format from the CDS website: "Copernicus Climate Change Service, Climate Data Store, (2021): (Accessed on DD-MMM-YYYY), 10.24381/cds.cf5f3bac"
Response: Will be revised as below.

Copernicus Climate Change Service, Climate Data Store, (2021): Global land surface atmospheric variables from 1755 to 2020 from comprehensive in-situ observations. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on 21-04-2025), 10.24381/cds.cf5f3bac

Figure 1: The dotted line in the legend is difficult to associate with the corresponding dashed color lines in the figure. It took considerable effort to interpret their meaning correctly. I recommend clarifying the legend by explicitly stating that solid lines represent the mean state and dashed lines indicate the trend (e.g., "(solid: mean, dashed: trend, left Y-axis)" after each color label), while shaded areas on right Y-axis. This would significantly improve readability and interpretation.

Response: We will revise the figure and caption to clarify.

Figure Caption: The 1991–2020 average ensemble spread of (A) mean annual air temperature (MAAT) and (B) relative maximum snow water equivalent (MaxSWE) among different reanalyses. The red (3DVar and 4DVar) and green (4DVar only) lines represent ensembles of differing numerical weather prediction models and assimilation systems, whereas the yellow line (ERA5) represents uncertainty in observations and physical parameterizations in a single modelling and assimilation system. **The solid lines represent the mean state and dashed lines indicate the trend (left vertical axis)**. Land area and population are shown for context **(right vertical axis)**. Values are summarized in intervals of 5 °C for the ensemble mean of MAAT. The occurrence of cryosphere elements, estimated as the probability of occurrence during the analysis period, is scaled per MAAT bin of 0.1 °C (see Methods). Only reanalysis cells with a significant ($P < 0.05$) trends are used for the analysis of change. Blue numbers express low population counts in million. The peak in the trend of MaxSWE observed for MAAT class from −15 °C to −20 °C is caused by increased uncertainty in ice-free areas of Greenland and Antarctic.

**References**


Rantanen, M. et al. The Arctic has warmed nearly four times faster than the globe since 1979. Commun. Earth Environ. 3, 168 (2022).

Gruber, S. Derivation and analysis of a high-resolution estimate of global permafrost zonation. The Cryosphere 6, 1 (2012), 221-233.

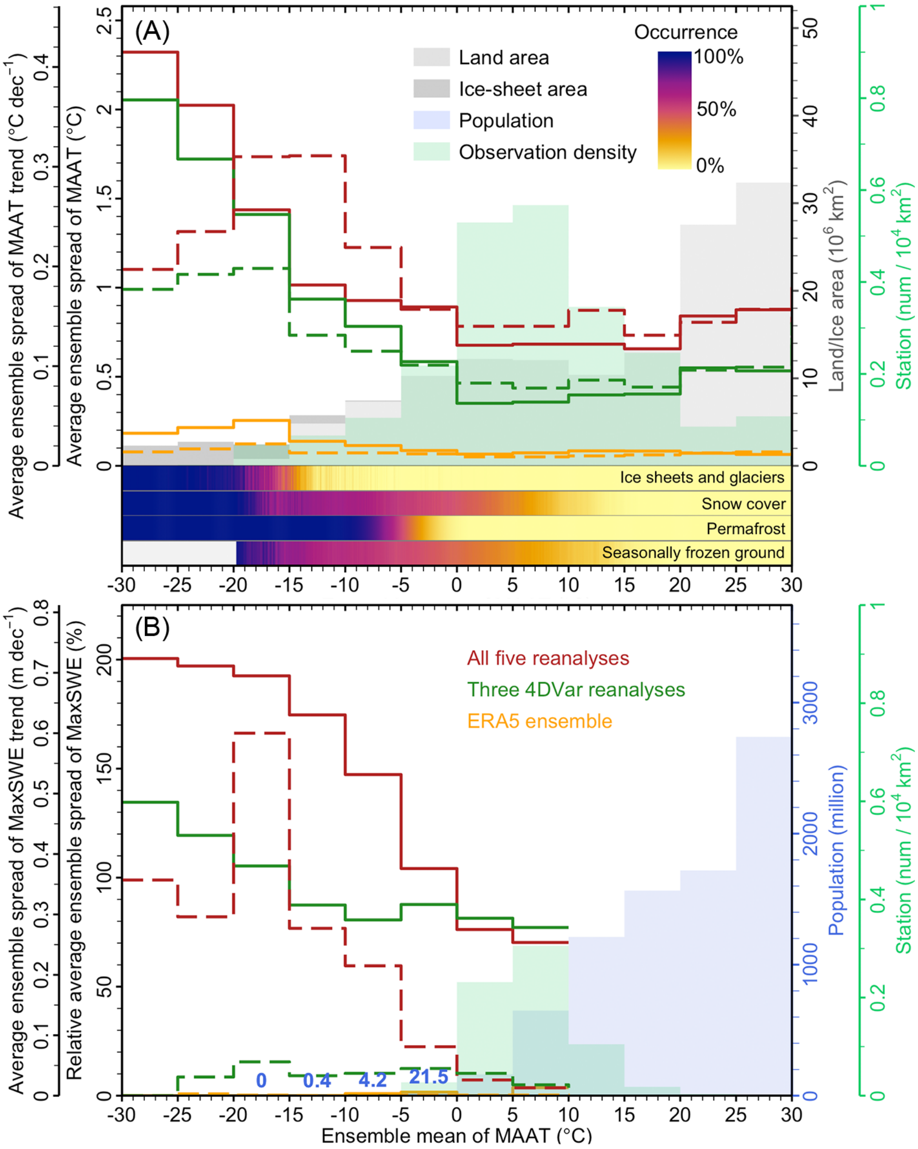


Figure 1: The 1991–2020 average ensemble spread of (A) mean annual air temperature (MAAT) and (B) relative maximum snow water equivalent (MaxSWE) among different reanalyses. The red (3DVar and 4DVar) and green (4DVar only) lines represent ensembles of differing numerical weather prediction models and assimilation systems, whereas the yellow line (ERA5) represents uncertainty in observations and physical parameterizations in a single modelling and assimilation system. **The solid lines represent the mean state and dashed lines indicate the trend (left vertical axis).** Land area and population are shown for context **(right vertical axis)**. Values are summarized in intervals of 5 °C for the ensemble mean of MAAT. The occurrence of cryosphere elements, estimated as the probability of occurrence during the analysis period, is scaled per MAAT bin of 0.1 °C (see Methods). Only reanalysis cells with a significant ($P < 0.05$) trends are used for the analysis of change. Blue numbers express low population counts in million. The peak in the trend of MaxSWE observed for MAAT class from $-15$ °C to $-20$ °C is caused by increased uncertainty in ice-free areas of Greenland and Antarctic.

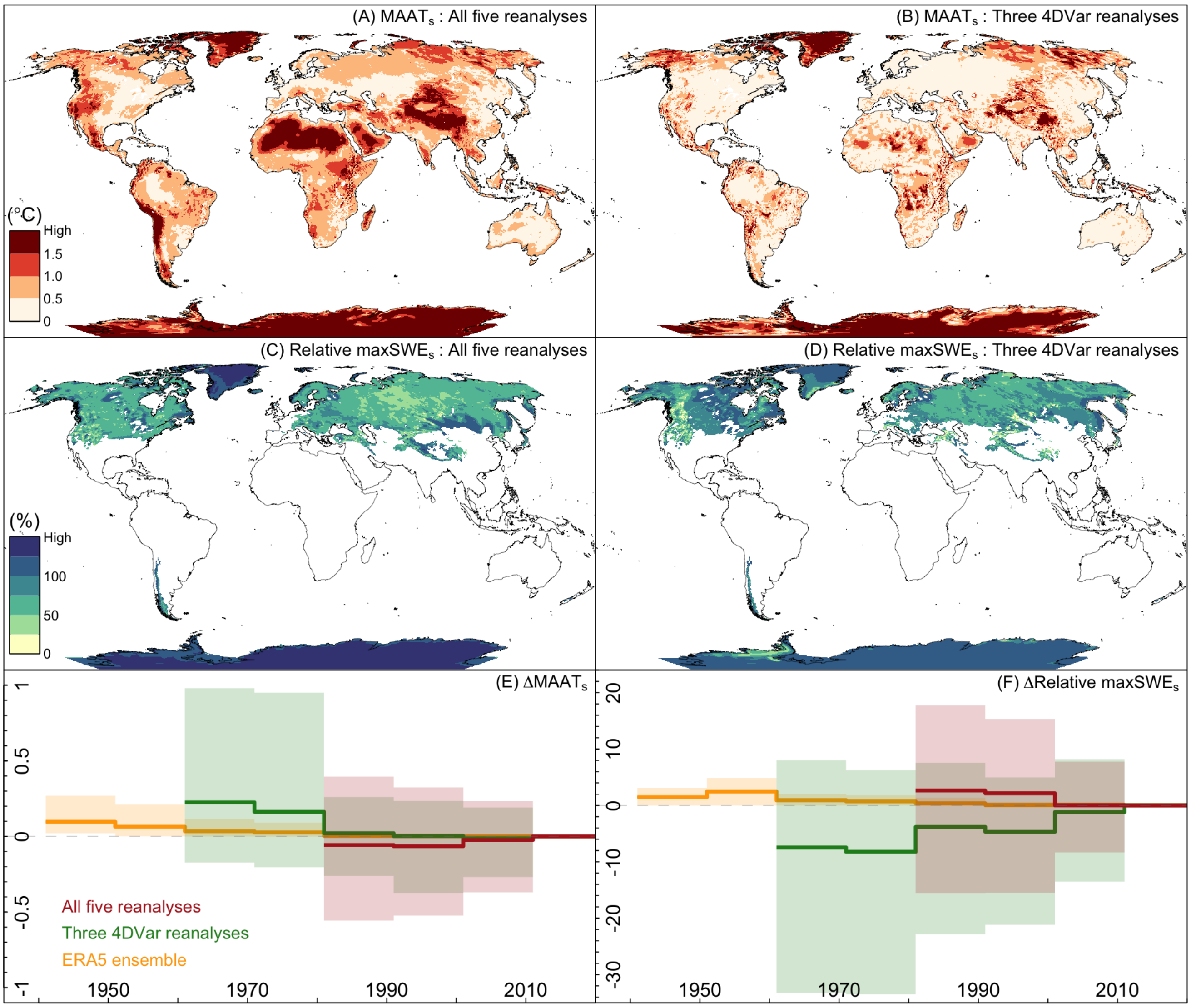


Figure 2: The 1991–2020 average ensemble spread of mean annual air temperature ($MAAT_s$) and relative spread of maximum snow water equivalent ($maxSWE_s$). Only areas with a mean $maxSWE_s$ greater than 0.0125 m (0.05 m snow height at a snow density is 250 kg $m^{-3}$) are shown. Snow water equivalent is not available for the two continental ice sheets in MERRA-2, and therefore, not included in these regions. The overall temporal changes for (E) $MAAT_s$ and (F) relative $maxSWE_s$ was derived with the reference period of 2011–2020, and a positive value means the spread is reduced relative to the referenced period. In E and F, the solid lines represent the mean state and shaded areas indicate 10th to 90th percentile. The difference between all five reanalyses and three 4DVar reanalyses is given in Fig. S2.

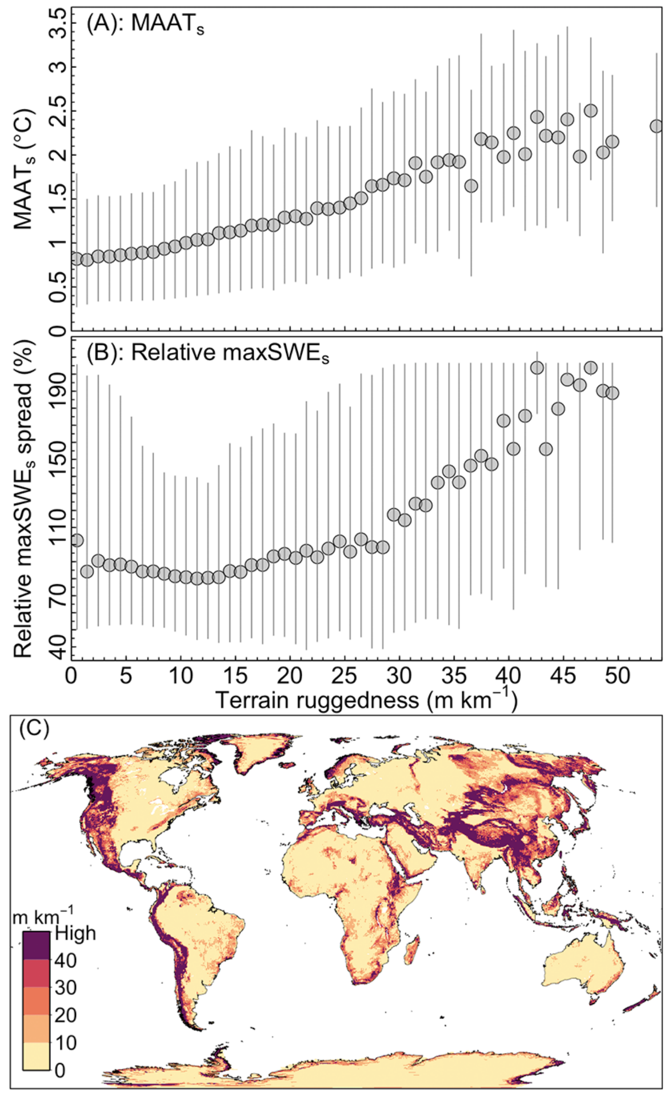


Figure S3: The changes of ensemble spread for (A) mean annual air temperature (MAAT) and (B) relative maximum snow water equivalent (maxSWE) as a function of (C) terrain ruggedness. The points represent the mean spread and lines indicate 10th to 90th percentile.