The Cryosphere Discuss., author comment AC2
https://doi.org/10.5194/tc-2022-5-AC2, 2022


# Reply on RC2

Tyler C. Herrington et al.

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Author comment on "Validation of pan-Arctic soil temperatures in modern reanalysis and data assimilation systems" by Tyler C. Herrington et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2022-5-AC2, 2022

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The authors would like to thank Referee 2 for their helpful comments. As a part of our revisions, we have gathered substantially more data for North America, and have recalculated all metrics. In our updated database, we now have 135 validation grid cells over North America; 30 of which are located over the permafrost region. By utilizing soil temperature data from a variety of hydrometeorological and agricultural monitoring networks, our dataset now provides the most comprehensive analysis to date of soil temperatures across northern and southern Canada and the Great Lakes basin.

## Major Comments

- The authors list potential future applications of the ensemble mean product, but I would wish to see a bit more discussion on its current usability, given that the recorded biases remain quite high and display some regional patterns. The underlying reasons for these are addressed in the manuscript but not how the biases would affect, e.g., permafrost simulations where a bias or RMSE of above 2° C can have notable implications.

We thank the reviewer for this comment. Several of the products have an RMSE of ≤4$^{o}$C – particularly over permafrost regions (as shown in S1). In most products, this is expressed as a cold bias, which would suggest that reanalysis products may overestimate permafrost extent and underestimate active layer thickness. The ensemble mean biases and RMSE are generally better than (or similar to) the best performing product, especially when all seasons and depths are considered. In addition, the ensemble mean soil temperatures show a more realistic pattern of soil temperature variability in the permafrost zone compared to the individual products themselves.

The ensemble mean product provides gridded, monthly-averaged soil temperature estimates of near surface, and deeper soil temperatures at a 1$^{o}$ resolution. Therefore, it is most suitable to regional or hemispheric-scale analyses of soil temperature climatologies, or their seasonal cycle, or to explore recent trends in soil temperatures (since 1980). The product could also be used to provide boundary conditions for hydrological models. In fact, a higher resolution version of this product (see our response to Question 12 in Minor Comments) is being used for such a purpose and will be described in a follow-up study.

The authors acknowledge that the ensemble mean soil temperature product would most likely yield an overestimation of permafrost extent, given that it is biased cold by 3-5$^{o}$C, on average, at high latitudes. That being said, over permafrost regions, the RMSE of the ensemble mean product outperforms the RMSE the best performing product by ~2$^{o}$C, on average, and hence it may still provide some added value for estimation of high latitude soil temperatures relative to the individual products.

- At places the text is hard to follow (especially Section 4.3, see detailed comments below) owing to the multiple simultaneous comparisons: near surface vs. at depth soil temperatures, cold season vs. warm season, permafrost vs. no to little permafrost, North America vs. Eurasia, and DJF vs. JJA. I suggest the authors to make sure all sections are clearly defined.

We will restructure the results section to make things clearer. The general delineation will remain the same, with a pan-Arctic assessment (section 4.1 – Warm Season and section 4.2 – Cold Season), and a permafrost-focused section (section 4.3), as we believe that this is a natural way to delineate the results, but we will try to more logically separate the near-surface results from the results at depth. We will also separate out the regional results, especially now that we have a greater number of validation grid cells over North America (making the comparisons between Eurasia and North America more meaningful).

- L104: The authors suggest that their study is"To the authors’ knowledge, this one of the first studies to compile a comprehensive set of in situ soil temperature measurements across the Eurasian and North American Arctic, from multiple diverse sparse networks". While it may be true that this is true for the “one of the first” part, it should be noted that the compilation is not totally novel, given that similar in situ temperature datasets have been compiled not only by Cao et al. (2020, in the references) but also, e.g., by Karjalainen et al. (2019) and Ran et al. (2022) who used mostly the same data sources, albeit computing temperatures averages for a much larger depth (several meters deep in permafrost but also in non-permafrost soils). Moreover, Lembrechts et al. (2020) have published a global soil temperature compilation of soil and near-surface temperatures. I suggest the authors to consider if their statement needs some elaboration, e.g., does the compiled dataset differ from previous datasets in some ways.

The authors recognize the notably different sampling size for North America but retain from explaining why no more data were collected, apart from mentioning the overall data scarcity in northern Canada, to correct the imbalance between North America and Eurasia. Based on the previous data compilations (see above), there should be suitable measurement time series available from North America.

The authors thank the reviewer for making us aware of these studies. As a result, the biggest change in the revised manuscript is the inclusion of a large amount of new soil temperature data from North America. Figure R1 compares the previous and updated distribution of validation grid cells, which now contains 135 validation grid cells over North America near the surface; 30 of which are located over the permafrost region. This means that our sample of sites for North America is now more comparable to the 247 grid cells in Eurasia (45 of which span the permafrost region).

The new data are drawn from multiple sources, and we reiterate our claim from the original manuscript that this collection of pan-Northern Hemisphere soil temperature data constitutes a novel and important contribution to the permafrost research community.

Over the permafrost region, we've assembled data from the Yukon (Yukon Geological Survey, 2021) and the NWT (Cameron et al., 2019; Ensom et al., 2019; Gruber et al., 2019; GTN-P, 2018; Spence and Hedstrom, 2018a; Spence and Hedstrom, 2018b; Street, 2018).

In addition, we have incorporated data from several soil monitoring and hydrometeorological networks across Southern Canada and the Great Lakes basin of the United States, that, to our knowledge, are not included in any of the above papers. These include 85 stations from the Manitoba Mesonet network (RoTimi Ojo and Manaigre, 2021), 83 stations in Michigan and western Wisconsin (MAWN, 2022), 31 stations from the Alberta Climate Information Service network (Alberta Agriculture, Forestry and Rural Economic Development, 2022), and 150 stations from North Dakota (NDAWN, 2022). We are also including data from a peatland ecosystem in Metro Vancouver (Lee et al., 2017; Lee et al., 2021), as well as data from 11 stations in central and Northern BC (Déry, 2017; Hernández-Henríquez et al., 2018; Morris et al. 2021), and 2 stations in southern Quebec (Arsenault, 2018; Fortier, 2020).

We have also been in contact with the data providers from the Real Time In-Situ Monitoring Network (RISMA), however the data was not available to include at the time this response was submitted. We hope to include the RISMA dataset (which includes 13 stations in southern Manitoba, 6 stations in southeastern Ontario, and 4 stations in southern Saskatchewan) in follow-up studies.

While the Ran et al. (2022) study included borehole measurements from southern Canada, the data did not include information about the seasonal cycle of soil temperatures. Thus, our work presents the most comprehensive analysis to date of soil temperatures across northern and southern Canada and the Great Lakes basin.

**Minor Comments**

- LL140-141:"Panel B of Figure 1 shows the spatial standard deviation of monthly surface soil temperatures for grid cells with more than two stations included." However, in Figure 1b, grid cells with two stations are also shown. Also, I remain unsure whether there are any grid cells with >1 stations in Eurasia?

This was a typo. It should read "Panel B of Figure 1 shows ... grid cells with **two or more** stations included."

Based on the grid cells that met our criteria for validation, there were no grid cells in Eurasia with two or more stations included. A clarification has been added to the text.

- L236: Reference should be to Fig. S1, right?

L236 mentions that "several factors may explain the increased variability in soil temperatures over permafrost regions." We presume that you may have meant L226, which describes the difference in the mean bias/RMSE over North America versus Eurasia?

Figure S1 displays the mean bias and RMSE over the combined Pan-Arctic permafrost zone. Here we meant to refer to Figure S2, which shows the difference in bias between Eurasia and North America. We will make this correction in the revisions.

- L239: What correlations, the ones between measurements and reanalysis temperatures? A slight elaboration would help the reader to see that what are compared in the sentence.

Yes, these are referring to correlations between the observed soil temperatures and the reanalysis temperatures. We will rephrase this sentence to "Correlations between observed soil temperatures and soil temperatures in the reanalysis products are generally quite similar in both the permafrost region and zone with little to no permafrost."

- LL240-241: I also struggled with this sentence. What is the opposite situation here? It is hard to follow the comparisons between permafrost and little to no permafrost, as well as near-surface and at depth temperatures at the same time, especially since the results are not shown.

Here we were referring to the fact that the reanalysis products are more likely to overestimate the observed variance over the permafrost region at depth. We will split L240-241 into two sentences. "Individual models are more likely to overestimate the near surface soil temperature variance over the zone with little to no permafrost. At depth, however, reanalysis products are more likely to overestimate the variance over the permafrost region."

- LL243-246: Are these results related to the permafrost binning? It's fine if they are not, but overall Section 4.3 is at times hard to follow because it deals with both permafrost binning and regional comparisons.

We have revised Section 4.3 to focus entirely on permafrost regions so that this, and other, ambiguities in this section are corrected.

- L405: Instead of the cold season standard deviations, should you not refer here to cold stations/observations? That is, figure 6 does not distinguish between warm and cold season.

What we were describing here is that when soil temperatures are frozen (and particularly for soil temperatures below $-20^{o}$C), soil temperature standard deviations increase to near $10^{o}$C in several products. We will make this clear that we are explicitly referring to frozen soil conditions.

- L261: The ensemble mean product is not properly addressed until deep into the results (validation) section. I suggest presenting the ensemble mean product and its calculation procedure already in the early stages (possibly inside section 2.1.).

As suggested, we will add some further details about the methodology used to create the ensemble mean soil temperature product in Section 3 (Methods).

- L303: I find "coastal regions" not the ideal term here because the regions with the highest variability are far more than that. In winter, greatest variation associates with the coldest regions, yet not exclusively either. Could the variation here be related to snow cover duration / snow thickness as mentioned elsewhere in the text?

We agree that "coastal regions" does not adequately describe the spatial pattern of variability – particularly in winter – and we have changed the description to "colder regions" in the revised text. Figure R2 shows a scatterplot of the relationship between mean annual air temperature (MAAT) and soil temperature standard deviation, when soil temperature variance is largest. The figure shows that soil temperature standard deviation and MAAT have a moderately strong negative correlation of -0.69. Moreover, it appears that regions with extreme continentality (such as eastern Siberia) show the largest standard deviations. While it is possible that snow cover characteristics may be important in certain regions, a detailed snow cover analysis is beyond the scope of this paper – and will be the focus of a follow-up paper.

**Technical Corrections**

- L61: Please, open the abbreviation GLDAS-CLSM already here.

We will expand GLDAS-CLSM to read "Global Land Data Assimilation System – Catchment Land Surface Model" here.

- LL80-83: Check grammar of the sentence. Maybe delete the word "that" at line 81?

This sentence should say "In ERA5, a weak coupling exists between the land surface and atmosphere. It includes an advanced LDAS 80 that incorporates information regarding the near-surface air temperature, relative humidity, as well as snow cover (de Rosnay et al., 2014), along with satellite estimates of soil moisture and soil temperature from the top 1m of soil (de Rosnay et al., 2013)."

- L191: Figure 2 does not have panels C and D.

This sentence should read "Warm season biases tend to be slightly larger at depth (Figure 2, Panel B) for most products (by 1$^{o}$C – 2$^{o}$C)."

- Figure 3: This is a nice figure with lots of information in it. The letters in "Correlation coefficient" are clumped together and could be corrected.

This will be improved in the revised version.

- Figure 4: Stratification of the values in histograms is not explained. Please add it to the caption.

The data in the histogram are stratified based on the Berkeley Earth Surface Temperature (BEST) 2m air temperature. The cold season (blue) refers to soil temperatures occurring when the air temperature is ≤ -2$^{o}$C, while the warm season (red) refers to soil temperatures when the air temperature is > -2$^{o}$C. We will ensure that this is included in our revisions.

It is also now apparent that there is a typo in this caption. It should have read “Seasons are stratified by the BEST air temperature, with the cold season (≤ -2◦C) in green and the warm season (>-2◦C) in red.”

- Figure 5: Y-axis is a bit messy. Consider adjusting the interval at which temperatures are denoted.

We will change the Y-Axis to include major ticks at every 2◦C, which should hopefully declutter the Y-Axis.

- Figure 8: DJF missing from Panel A label.

Figure has changed in response to other revisions: captions/labels will be corrected as appropriate.

- L286: NH -> northern hemisphere

We will expand NH to read “northern hemisphere” here.

- L290: Why are ensemble mean at depth temperatures not shown? Could be part of the supplement. Figure 9 also shows at depth results, so it would be interesting to see how the models reconstruct frozen ground in JJA, although it is acknowledged that this is not explicitly representative of permafrost.

Our decision to not include the results at depth was because the pattern correlations were quite similar to those near the surface (with a pattern correlation of ~0.95 over the study area). The overall features were generally quite similar, however showing a smaller annual range of temperatures. We have added a sentence explaining our reasoning behind the decision to focus on the near surface, but will include the depth results as a supplemental figure.

- L366: Please put Gruber et al. 2018 inside parentheses.

We will change “Gruber et al. (2018) to “(Gruber et al., 2018)”.

- L369-370:"Moreover, the impact of snow cover on soil temperature is generally more pronounced over permafrost regions (regions of seasonal frost).“ Is something missing here? Should it be "compared to regions of seasonal frost" or what is the idea?

We agree that this sentence is confusing. It should read “Moreover, the impact of snow cover on soil temperature is generally more pronounced over permafrost regions relative to regions of seasonal frost.”

- LL418-419: Could you elaborate, what does it mean "is being explored"?

Using a similar blending methodology, we have been investigating the performance of a 0.31-degree product (using a smaller subset of products that provide data at higher spatial resolution). We have also performed similar analyses with a 0.05-degree soil temperature product, using interpolated soil temperatures from the Arctic System Reanalysis version 2 (ASR), ERA5-Land, and the Famine Early Warning Systems Network (FLDAS). The goal has been to assess the impact of spatial resolution on performance of the ensemble mean product. We are hoping to include these results in a follow-up paper.

- L428: Please provide a url for the ensemble mean dataset on the ADC.

The original version we submitted had all URLs as hyperlinks. We see that the hyperlinks are not present in the version available online, so we will be sure to include a URL for the dataset in our revisions.

- L583: Database title and url missing.

We will be sure to correct this and include a proper link to the Arctic Data Center repository for the Kropp dataset.

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Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2022-5/tc-2022-5-AC2-supplement.pdf