The authors would like to thank the reviewer and editor for their constructive feedback, and the thorough assessment of the manuscript. Below we provide a point-to-point response to each comment, reviewer comments are given in black, responses are given in blue.

Responses of Anonymous Referee #1

The study "The ERA5-Land Soil-Temperature Bias in Permafrost Regions" by Cao et al. evaluates the performance of the ERA5L reanalysis for ground temperatures and other ground-temperature-related parameters in permafrost areas. Although ground temperature is not a main target parameter for such reanalysis products, the study will be a valuable scientific contribution and I recommend publication after carefully revising the manuscript.

Major Comment/Recommendation:

When reading through the manuscript, many important points only became clear to me very late, i.e. in the Discussion. The temperature comparisons of the different products in the Results section, for example, left me wondering on the interpretation and implications. The same applies to the findings on the sizable reduction of "permafrost area" in ERA5L, which only much later is resolved as likely being more an artefact of the model than reality. To a casual reader, the manuscript appears to make a number of potentially bold statements, without providing any hint that the interpretations/ clarification of implications are provided at some later stage in the Discussion (where some casual readers might miss it). While the strict separation of the different manuscript parts is in line with accepted methodology for scientific writing, I recommend guiding the reader through the manuscript in a better way. I have made more specific annotations and suggestions under general comments.
We agree, hints are added as suggested in the specific comments. Especially, Section 5.2 is mentioned in the caption of Table 2 in order to avoid any possible misunderstanding. We moved the implication part from Section Conclusions to the Discussion (Section 5.5).

General comments:

Sect. 2.2 Remind the reader in one sentence what HTESSEL is, this is somewhat hidden in the previous text.
We changed this part to *"... A more realistic representation of snow is used in the ERA5 land surface model compared with its predecessor, ERA-Interim."*

Sect. 2.3 and 3.1: Please add information on the depths of the available borehole temperatures and how this compares to the shallow ground representation in ERA5L. The Biskaborn-data set, for example, contains many borehole measurements at much deeper layers than ERA5L can represent, so (how) are these measurements used?
Only the observed temperature within the ERA5L soil temperature column, i.e. 0–2.89 m, were used here. In Table 1, we added the depth range of used soil temperature observations for each data source. In Section 3.1, we revised as *"For the purposes of evaluation, temperature observations were only used from depths between 0 m and 2.89 m, corresponding to the range of the ERA5L soil column. Temperature values were grouped according to their depth into one of the ERA5L soil layers."*

l.112: the first criterion is unclear, is this "if T of any of the four layers is constantly below zero for two years"?
Yes. It is changed as *"An ERA5L grid cell is considered to be underlain by permafrost if either of the following conditions are true: (1) soil temperature in any of the four soil layers has an hourly temperature below 0 °C for two consecutive years (ERA5L$_H$)"*

Sect. 3.2 The added value of this is unclear at this stage of the manuscript, it seems to be rather unrelated to the main purpose, i.e. compare the direct ground T output of ERA5L to observations. This becomes clear only much later, but please add a few sentences on the purpose already here.
At the beginning of Section 3.2, we added *"Our results show remarkable bias of ERA5L soil temperature in winter that likely correlates with snow depth (Figure 2). For this reason, the suitability of ERA5L soil temperature and the effect of snow-density bias are further investigated with a site specific simulation example at a densely instrumented location near Lac de Gras (LdG), N.W.T., Canada (Figure 1A). This detailed permafrost simulation example provides an opportunity to evaluate ERA5L soil temperature under different terrain (e.g. vegetation, soil properties) and snow conditions."*

Table 2+3: add the references to the different products used (at least in the caption), so that the readers don't have to search for the abbreviations in the text.
The reference is added in the caption:

> Table 2: *"...The $MAGT_{avg}$ is the average MAGT: 2001–2018 for ERA5L, 2000–2014 for the CP map (Karjalainen et al., 2019), and 2002–2016 for the TTOP map (Obu et al., 2019)."*
>
> Table 3: *"Note that the CP map only represents permafrost distribution north of 30° N (Karjalainen et al., 2019), TTOP map represents permafrost distribution of the Northern Hemisphere (Obu et al., 2019), and the others represent the area of north of 60° S. Permafrost area from literature is given with their definition in this study.*

l. 129: the purpose of the equation is unclear, and must be explained in more detail.
To clarify the purpose, we conducted revision below.

1) refer to Eq. 1 in Section 3.1: *"MAAT bias and maximum snow depth (SD_{max}) were selected as candidate variables to be assessed as possible predictors of ERA5L soil temperature bias (see Eq. 1)"*.
2) this sentence is changed to *"The following linear model was used to predict ERA5L soil temperature bias in permafrost regions using MAAT bias and snow depth as predictor variables."*.

If I understand correctly, you relate the bias in MAGT to the bias in MAAT, using the snow depth (which has no bias, I guess since measurements are not available?).
Yes, snow measurements are not available.
Does the intercept of 0.15 make sense, i.e. zero bias in MAAT and zero snow produces an MAGT bias of 0.15? Should one not rather prescribe an intercept of 0 in the equation? I guess it would not change much, considering the R2 of 0.47 of the relationship.
We can expect uncertainty of the linear model with R^2 of 0.47 since it was fitted with limited observations, i.e. 239 grid cells. However, the intercept of 0.15 makes sense. It means even no MAAT bias and snow cover is present, ERA5L soil temperature in permafrost regions could still have bias that may from the other variables, i.e. due to the mismatched depth of observations and ERA5L soil layer.

Table 2: I assume the comparison is done for the individual years when- and wherever an entire year of observations is available?
Yes, for MAAT, SO, and MAGT evaluation, the comparison is done for individual available years, while the $MAGT_{avg}$ is the average MAGT for the entire long period. In the caption, we added *"MAAT, SO, and MAGT were evaluated for each individual year, while $MAGT_{avg}$ was carried through once for the entire period and are based on sparse data."*
How does this relate to CP and TTOP which represent longer periods, are only observation that span the entire periods used? If not, to what extent does the availability of observations influence these comparisons - many observations are likely taken in recent years, which on average were warmer than earlier periods. There is the passage starting with "Note that the performance of CP and TTOP maps may be lower here than reported in: : :", but the implication of this is not really clear.
In Section 3.1, we added *"The TTOP and CP map were derived using an equilibrium model, and MAGT is given as an average of the entire period ($MAGT_{avg}$). This corresponds to 2002–2014 for the CP map and 2002–2016 for the TTOP map, without uniform/specific soil depth. To better evaluate, we aggregated all available observed MAGTs during the period by averaging, and then compared against the $MAGT_{avg}$ of these two maps. Note that the performance of CP and TTOP maps may be lower here than reported in the original publications due to the fact that we evaluate them with a different set of observations (different depths, periods and proportion of sites in mountains)."* to clarify. The sentence of *"Note that the performance of CP and TTOP maps may be lower here than reported in..."* is removed from Section 4.1

Table 2 seems to suggest that ERA5L is considerably better than CP and TTOP for PF areas, but it is unclear if that conclusion can indeed be drawn. This is not only considering the study periods, but also the spatial distribution of the measurement sites (heavily biased towards China, SE Russia and Alaska according to Fig. 2). This point is adequately discussed in 5.2, but it would be good if some of it could be mentioned already here. At least include a statement "see Sect. 5.2 for a detailed discussion" in the text.
Yes, the summary statistics with sparse data would be misleading. In the revision, we added *"$MAGT_{avg}$ must be interpreted cautiously, taking into consideration the points outlined in Section 5.2."* in the caption of Table 2.

l. 137: typo “bilinearly”
Revised.

Fig. 1: add units in the figure.
The unit, °C, is now included in the legend.

Fig. 2 is only presented in one sentence in the text. This should be presented in more detail. I suggest using this to motivate Section 4.3 (see also comment above).
Figure 2 is added in Section 3.2: *"Our results show remarkable bias of ERA5L soil temperature in winter that is thought to correlate with snow depth (Figure 2)."*

Table 4: Are there any snow density measurements from the site that could clarify which one of the models is right (or if both are wrong).
There's no snow measurements used here. As we've stated *"While we do not imply that the GEOtop simulations are correct or accurately represent metamorphism in Arctic snow (see Domine et al., 2019), they do demonstrate that simulations with snow cover of similar mass but different density are able to match ground-temperature observations far better than ERA5L."*. In fact, simulating critical snow physical variables in Arctic is challenging (see Domine et al., 2019).

l. 152: Make it clear that this is “ERA5L PF extent as defined in this study”, it is clear that the shallow soil column makes it very difficult to relate this to “true PF extent change”. Such statements can easily be misunderstood, compare to “Lawrence, D.M. and Slater, A.G., 2005. A projection of severe near-surface permafrost degradation during the 21st century. Geophysical Research Letters, 32(24).” and the resulting comment by Burn & Nelson. This issue is again explained later in the discussion, but make it clear already here, that this by no means represents real PF extent changes.
It is changed as *"Near-surface permafrost area of ERA5L as defined in this study decreased at a rate of -0.11 (-0.08) $\times 10^6$ km^2 year^{-1} based on hourly (annual) mean soil temperature."*

l. 168: what do you mean by “although less permafrost processes are coupled”?
Compared to CLASS-CTEM presented by Melton et al., (2019), HTESSEL includes less physical processes regarding permafrost. We changed this part to *"Compared to a coarse-grid (∼2.8°) simulation (Figure 4 from Melton et al., 2019), ERA5L often has more reasonable results in its deepest soil layer, despite the fact that fewer permafrost-specific physics are included in the HTESSEL. "* to clarify.

L. 170: When I look at Fig. 5, I don't quite understand why there is a “remarkably low bias in PF extent”. Your explanations later seem to go in the direction that this might rather be a coincidence, since biases in different regions cancel each other?
The low bias of ERA5L summary statistics in Table 2 is a coincidence as the warm bias in high latitudes (Canada and Alaska) and cold bias in mid-low latitudes canceled each other (Figure 3). The "remarkably low bias in permafrost area" is because 1) ERA5L can only represent the "near-surface" permafrost area due to the shallow soil column; 2) warm bias of soil temperature in high latitudes, especially in northern Canada and Alaska (Figure 1).
Furthermore, ERA5L cannot really represent the discontinuous and continuous permafrost zones, so fractional PF coverage is by definition not included.
The 50% permafrost coverage is used for the IPA map regarding continuous and discontinuous permafrost. Details are present in Section 2.4: *"Following Melton et al., 2019, we apply a threshold of 50% (corresponding to the continuous and discontinuous permafrost zones) and 0.5 for the IPA map and the PZI map, respectively, to allow for meaningful comparison with the other maps."*

Sect. 5.4: Dedicated snow models like CROCUS and Snowpack also include formulations for compaction due to wind drift which likely occurs at LdG(?). If I understand correctly, this is neither included in the ERA5L model nor in GEOtop? This should be stated, especially since there seem to be no field measurements of snow densities from the site which could clarify which model is more right? I would certainly agree that the GEOtop snow densities look much more realistic, but that's more an educated opinion, rather than science.
The snow compaction due to wind effects is represented in GEOtop (2.0) following Pomeroy et al., (1993), while not in the ERA5L. We considered the wind compaction for all terrain types in LdG except the tall shrubs site. In section 3.2, we added *"Snow compaction due to wind effects is considered in 1-D for all terrain types except for the tall shrub site (Pomeroy et al., 1993)."* to clarify. In addition, we changed the last sentence to *"An additional contribution of GEOtop to higher snow densities in tundra environments may be*

the effect of blowing snow (cf, Pomeroy et al., 1993)" to clarify.

Discussion general: Consider adding a Section "Implications" or similar – especially the findings on the snow cover and the shallowness of the ground representation are very interesting also for improvements of further reanalysis generations. To me it almost looks like that one might get a pretty good performance for permafrost parameters by doing a couple of obvious improvements of the ground and snow models (which likely wouldn't even cost a lot of additional computation). You study is a great reference for this, and stating this clearer will likely increase the impact of the paper.
The implications was given at the end of the manuscript as part of the conclusions. We now moved this part to the new Section 5.5 Implications (as below) in order to make the manuscript more readable:
"While global reanalyses provide urgently needed meteorological drivers for permafrost simulation, their soil data is not well suited for directly informing permafrost research or local adaptation decisions. As such, simulations using permafrost-specific land-surface models driven by reanalyses (Cao et al., 2019a, Fiddes2015) will likely be increasingly important in the provision of permafrost climate services. Making future soil-temperature products like ERA5L directly usable will require significant permafrost-specific alterations in model design, especially with respect to snow cover and the total depth of the ground representation for the land-surface models that are used. If indeed the value of the parameter c_ξ in the snow metamorphism of HTESSL is in error, then this would be an easy improvement."

References

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Domine, F., Picard, G., Morin, S., Barrere, M., Madore, J. B., and Langlois, A.: Major Issues in Simulating Some Arctic Snowpack Prop- erties Using Current Detailed Snow Physics Models: Consequences for the Thermal Regime and Water Budget of Permafrost, Journal of Advances in Modeling Earth Systems, 11, 34–44, https://doi.org/10.1029/2018MS001445, 2019.

Karjalainen, O., Aalto, J., Luoto, M., Westermann, S., Romanovsky, V. E., Nelson, F. E., Etzelmüller, B., and Hjort, J.: Data descrip- tor: Circumpolar permafrost maps and geohazard indices for near-future infrastructure risk assessments, Scientific Data, 6, 1–16, https://doi.org/10.1038/sdata.2019.37, 2019a.

Melton, J. R., Verseghy, D. L., Sospedra-Alfonso, R., and Gruber, S.: Improving permafrost physics in the coupled Canadian Land Surface Scheme (v.3.6.2) and Canadian Terrestrial Ecosystem Model (v.2.1) (CLASS-CTEM), Geoscientific Model Development, 12, 4443–4467, https://doi.org/10.5194/gmd-12-4443-2019, 2019.

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., Khomutov, A., Kääb, A., Leibman, M. O., Lewkowicz, A. G., Panda, S. K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T., Yamkhin, J., and Zou, D.: Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale, Earth-Science Reviews, 193, 299–316, https://doi.org/10.1016/j.earscirev.2019.04.023, 2019.

Pomeroy, J. W., Gray, D. M., and Landine, P. G.: The Prairie Blowing Snow Model: characteristics, validation, operation, Journal of Hydrology, 144, 165–192, https://doi.org/10.1016/0022-1694(93)90171-5, 1993.

Responses of Anonymous Referee #2

General comments:
This paper presented a good assessment of the soil temperature at a large scale using in-situ observations and previous products/maps. Understanding current soil temperature bias in reanalysis could improve further Earth-system model design by accounting more essential permafrost processes and hence benefit the permafrost community. This paper is generally well written. I have some comments for further revisions.

Major comments:

- As Reviewer#1 stated, some important points became clear a little bit late. To casual readers, this may be not easy to follow.
  Please see our responses to the general comments of RC#1.

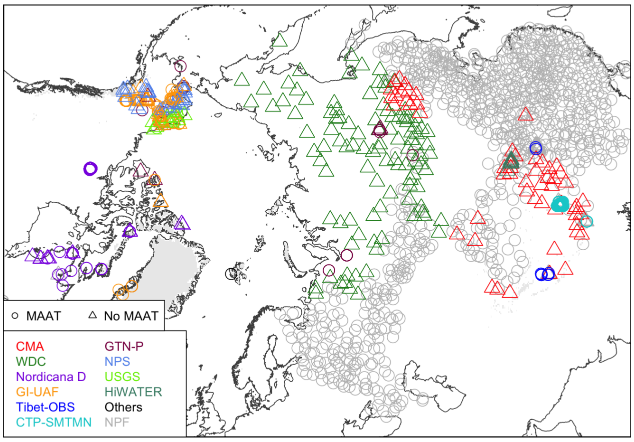

Figure 1: Distribution of soil temperature stations. Stations in permafrost regions are in color while the gray ones are non-permafrost (NPF) stations.Stations in circle additional has air temperature observation while the triangle ones do not.

- The authors MUST recheck this statement in L70–71. From the ERA5L website, they said: "Temperature of the soil in layer 1 (0–7 cm) of the ECMWF Integrated Forecasting System. The surface is at 0 cm. Soil temperature is set at the middle of each layer, and heat transfer is calculated at the interfaces between them." This is very important because these depths were used to interpolate soil temperature profiles and to determine ALT, if my guess is correct. If incorrect depths were used, the comparisons were already artificially altered.
  We've noticed the differences of soil depth from the ERA5L document website and model description document (see Table 8.7 in IFS Documentation CY45R1 (https://www.ecmwf.int/en/elibrary/18714-part-iv-physical-processes). We also contacted the scientist from ECMWF, and I simply copied the reply below.

  "The soil temperature of a given layer is an averaged value over of the thickness of that layer and assigned to the middle of the layer. From the modeling point of view this temperature is a valid temperature for any point in the layer, whereas in reality it'll be different depending on the depth. This is one of the limitations when the soil is discretised in a finite number of layers."

  For this reason, we followed the depth in model document as described in L70–71: *"The ERA5L soil column is discretized into four layers with node depths (layer boundaries) at 0.07 (0–0.07), 0.21 (0.07–0.28), 0.72 (0.28–1.00), and 1.89 (1.00–2.89) m"*

- The authors should describe the estimate of ALT by using ERA5L.
  In paragraph of section 3.1, we added *"ERA5L ALT was derived by linearly interpolating the ERA5L soil temperature-depth profiles."*

- Did the authors consider the uncertainties from vegetation?
  Our results indicated that the ERA5L soil temperature bias are mainly from the MAAT bias (Figure 1), and snow (see larger bias in winter from Figure 2, and Figure 6). That's why we considered the MAAT bias and snow as possible predictors rather than the vegetation, and the linear model of Eq. (1) indicated the success of variable selection. We hope you agree.

- In section 2.3, I miss a description of air temperature observation, while it is used for analyses of ERA5L soil temperature bias (i.e. in Table 1 and the linear model). Authors have to add a brief description here, and even show them in a proper way. This could be easily done, for example, by changing the shape of the station with both air and soil temperatures in Figure A1.
  In the revision, we added the air temperature observation info to Figure A1.

Specific comments:

P2, L27: The RMSE of reanalyses soil temperature? Please clarify.
Revised as *"For example, over the Qinghai–Tibetan Plateau (QTP), Hu et al.,(2019); Yang and Zhang (2018) reported that the root mean squared error (RMSE) of daily soil temperature from different reanalyses (i.e. ERA-Interim/Land, MERRA-2, and CFSR) ranged between 1.8–5.1 °C. This error is most often expressed as a cold bias."*

P2, L40: ... and example numerical or process-based simulation...
Revised.

P2, L57: Note that ERA5L is now available from 1981.
In the revision, we added *"Note that at the time of writing, only ERA5L data after 2001 have been released to the public and so this evaluation is conducted using data between 2001–2018."*.

P4, L86: The soil temperature from the TTOP and CP maps are used as comparisons, please as mention here.
In the revision, we added *"The mean annual ground temperatures (MAGT) from the TTOP and CP maps were also used to evaluate ERA5L."*

P4, L89: ...(denoted as PZI map)",".., should it be ";"? Similar in L91.
Revised.

P4, L97: The MAGT of TTOP and CP maps are additionally used as reference in your Table 1 and Figure 3. Please clarify here.
Mentioned, see the response to comment on P4, L86.

P5, L104: ...in the same ERA5L grid cell...
Revised.

P5, L107: ...of ERA5L soil temperature....
Revised.

P5, L126: there is a repeat of the "the".
Revised.

P5, L134: ...and (2) an increase of 1 m wSD_{max}
Revised.

P7, L149: Is the ALT also overestimated in high latitudes and underestimated in high altitudes?
It is difficult to say as most of the sites in mid-low are excluded before evaluation since their ALT $>$ 1.89 m. In this case, the evaluation shown here are generally for high latitudes (see Figure 5 for the site distribution of ALT $<$ 1.89 m). We changed the caption of Figure 4 to *"The observed sites are mainly located in high latitudes, and the distribution is present in Figure 5."* to clarify.

P10, L164: Also mention the high spatial (and maybe temporal) resolution here, this is one of the most significant features of ERA5 compared to the others.
Revised as *"ERA5L has a number of advantages for permafrost research; it provides a long historical record (back to 1950, eventually), high spatial resolution, and global coverage."*

P13, L215: ...for c_ξ in Eq. B5...
Revised.

P13, L216: It should be 150 kg m^{-3} based on Eq. B5, please double check.
Revised to 150 kg m^{-3}.

P14, L236: Underestimate permafrost...(what)? Permafrost area? Please clarify.
It is permafrost area, and is clarified in the revision.

P14, L252–253: The bracket is incomplete
Revised.

P14, L255: Brackets are needed here for the url.
Revised.

P15, L270: Add space between m and s^{-2}
Added.

P16, L278: ρ_ξ is not included in Eq. (B5).
The sentence ischanged to *"where the a_ξ, b_ξ, and c_ξ are constant values of 2.8$\times$10^{-6} (s^{-1}), 0.042 (–) and 460 (m^3 kg^{-1}) derived or modified from Anderson(1976) and Jordan et al. (1999)."*

P16, L280: Considering move $\Delta\beta_s = 0$ to the upper so that Eq B6 would be aliened with the state of Eq. B8 and B10
Revised.

P16, L297: ...ice density of 920...
Revised.

Specific comments:

- Table 1: This is only for the observations in permafrost regions. Please clarify in the caption otherwise including the observations in non-permafrost regions.
  Yes, this is only permafrost regions. The caption is changed to *"Summary of soil temperature observations in permafrost regions..."*

- Figure 3: In the caption, it should be "...(observation-ERA5L)..."
  Revised.

- Figure 6: Considering add unit to the permafrost area changing rate.
  Note that the original Figure 6 is deleted, as the ERA5L simulated soil temperature, therefore permafrost area, is not well.

Responses of Anonymous Referee #3

This paper assesses the utility of ERA5L soil temperature products for permafrost studies by using a wide range of global station data from both permafrost and non permafrost regions as well as detailed simulation experiments at a specific site. The authors find that ERA5L has large biases making the product problematic for permafrost studies. This study is a valuable contribution as we increasingly use reanalysis products for land surface modeling studies, especially at regional or global scales and insights into performance of these products are useful. Additionally, such studies may help to guide future developments in land surface schemes used in reanalyses. I recommend publishing after considering my (mainly minor) comments.
(in grammatical comments changes are CAPITALIZED)
The manuscript has been carefully edited by native speaker with strong permafrost background in order to improve the language.

1. l.3 "is predicted TO BE too warm...."
Revised as *"We find that ERA5L overestimates soil temperature in northern Canada and Alaska..."*.

2. l.19 "Reanalysis, ASSIMILATES"
Revised as *Reanalysis consists of assimilating a broad range...*

9. l.74 "These INCLUDE"
Revised as *"Of these, there are..."*.

13. l129 "A linear model..."
Revised as *"The following linear model..."*.

16. l.147 "While ERA5L does not have DATA allowing deep ALT values to be computed"
Revised as *"While ERA5L is not capable of representing deep ALT..."*.

26, l.232. use of "low" here is confusing. you are biased to low densities, you do not have a low bias. I would say "a low-density bias" to make it clear.
We would keep the sentences as its current format: *"ERA5L snow density is hypothesized to have a low bias, at least in high-latitude areas, explaining part of the warm bias in soil temperature." as the snow do have a low bias.*

3. l.28 what is ERA5-Interim/Land? Seems a confusion of the products
It was a typo, should be ERA-Interim/Land.

4. l.29 "consistently cold BIASED."
Revised to *"This error is most often expressed as a cold bias."*

5. l.54 I think the HTESSEL ref could do with a publication citation.
The latest ERA5 paper, Hersbach et al., (2020), that describes HTESSEL is added here.

6. l.57 now available from 1981.
In the revision, we added *"Note that at the time of writing, only ERA5L data after 2001 have been released*

to the public and so this evaluation is conducted using data between 2001–2018.".

7. Section 2.2.1 what do B1 and B2 refer to?
Revised to *"Appendix B1"* and *"Appendix B2"* to clarify.

8. l.71 is the node really at the lower boundary (0.07) in soil layer 1?
Reviewer #2 also mentioned this issue. We copied the responses here.

Based on the Table 8.7 in IFS Documentation CY45R1 (https://www.ecmwf.int/en/elibrary/18714-part-iv-physical-processes), the lower boundary is 0.07 m, although this is different from the description in ERA5L document website). We also contacted the scientist from ECMWF, and I simply copied the reply below.

"The soil temperature of a given layer is an averaged value over of the thickness of that layer and assigned to the middle of the layer. From the modeling point of view this temperature is a valid temperature for any point in the layer, whereas in reality it'll be different depending on the depth. This is one of the limitations when the soil is discretised in a finite number of layers."

For this reason, we followed the depth in model document as described in L70–71: *"The soil column of ERA5L is discretized into four layers with node depths (layer boundaries) of 0.07 (0–0.07), 0.21 (0.07–0.28), 0.72 (0.28–1.00), and 1.89 (1.00–2.89) m."*

10. Section 2.3 and Table 1 are all stations boreholes? If so perhaps explicitly state that.
No, some sites are from boreholes, e.g., GTN-P, but sites like CMA, HiWATER, are from soil temperature sensor of meteorological stations. In Section 2.3, we added *"Sites consist of both meteorological stations and boreholes."* to clarify..

11. l.90-91 and driven by ERA-Interim air temperature.
The TTOP map compiled by Obu et al., (2019) was driven mainly by MODIS LST, but the data gaps due to cloud cover was filled by downscaled ERA-Interim air temperature. Please see Section 2.2 and Figure 1 from Obu et al., (2019). In the revision, we changed the sentence to
"...(3) the 1-km Northern Hemisphere permafrost map Obu et al., (2019) which is based on the semi-physical Temperature at the Top Of Permafrost (TTOP) model (TTOP map) driven by Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature that filled by downscaled ERA-Interim air temperature;" to clarify.

12. l111-114: I don't quite understand the motivation for the two definitions of near surface permafrost I think a sentence explaining why you do this would be helpful for the reader.
The two algorithms are defined here to derived ERA5L soil temperature-based permafrost area. In the revision, this sentence is changed to *"The ERA5L near-surface permafrost area is evaluated using existing permafrost maps."*

14. l.137 What depth are these MAGT's? Averaged across time or space? Please provide a bit more detail here.
Reviewer #1 also had similar comment. We copied the response here as well.

In Section 3.1, we added *"The TTOP and CP map were derived using an equilibrium model, and MAGT is given as an average of the entire period ($MAGT_{avg}$). This corresponds to 2002–2014 for the CP map and 2002–2016 for the TTOP map, without uniform/specific soil depth. To better evaluate, we aggregated all available observed MAGTs during the period by averaging, and then compared against the $MAGT_{avg}$ of these two maps. Note that the performance of CP and TTOP maps may be lower here than reported in the original publications due to the fact that we evaluate them with a different set of observations (different depths, periods and proportion of sites in mountains."* to clarify

15. l.143 more prevalent snow and soil freezing in the model or in reality? Please clarify. If in reality, then permafrost regions do not necessarily have more prevalent snow than non-permafrost regions.
This is in the HTESSEL model or ERA5L based on the bias comparison of in permafrost and non-permafrost regions(Table 2; Figure 1). We revised this part to *"In addition to the worse performance of MAAT in these regions, the result suggests that HTESSEL may be less suitable for soil temperature simulation in areas with more prevalent snow and soil freezing. The large warm bias of ERA5L soil temperature during winter (Fig-*

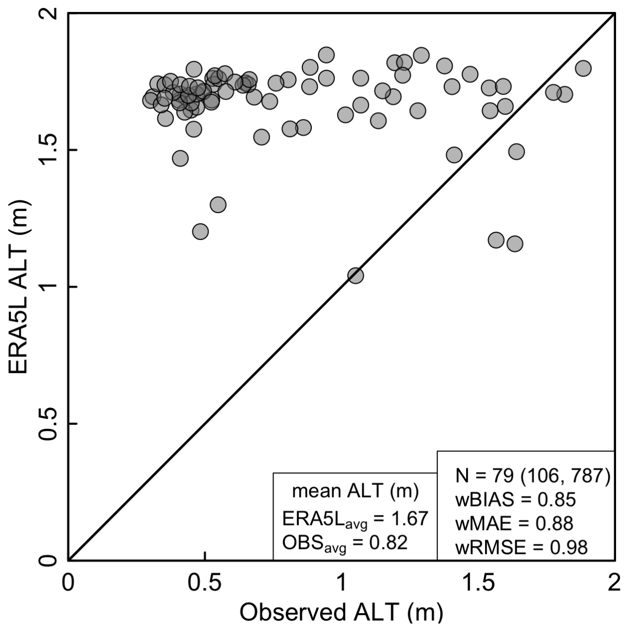

Figure 2: Comparison of shallow active layer thickness (ALT) based on 787 measurement from 106 stations located in 79 grids. The observed sites are mainly located in high latitudes, and the distribution is present in Figure 5.

ure 2) further supports this notion."

17. l.153 "(annually)" is it an annual average? Please clarify.
Yes, it is revised to *"Near-surface permafrost area of ERA5L as defined in this study decreased at a rate of -0.11 (-0.08) $\times 10^6$ km^2 year^{-1} based on hourly (annual) mean soil temperature. This corresponds to a loss of 1.7 (1.4) $\times 10^6$ km^2 of near-surface permafrost area since 2002. This is also suggested by the linear model." to clarify.*

18 Figure 3 Interesting latitudinal trend in c,d. Can you shed more light on this in the discussion? I guess densification processes at high latitudes (badly represented wind?) What is driving the cold bias at low latitudes?
As Reviewer #1 mentioned, HTESSEL does not have a representation of wind effects on snow densification. In this case, blowing snow. Both Figure 1 and the linear model (Eq. 1) indicated that the cold bias at low latitudes is largely due to the MAAT bias. In Section 5.1, we added
"Our results indicate that the cold bias of ERA5L in mid-low latitudes is highly aligned with the MAAT bias. This is also suggested by the linear model (Eq. 2)."

19. Figure 4 perhaps add the mean value that you cite in the text here.
Revised (see Figure 2 here).

20. l.170 "shows REMARKABLY"
Revised as *"ERA5L shows a remarkable underestimation of total permafrost area"*.

21. l.194 "Even for A"
Revised.

22. l.198 "This issue is KNOWN"
Revised.

23. l.208 "as AN exponential..."
Revised.

24. l.226 soil temperatureS MATCH..."
Revised as suggested.

25. l.230 But what about the cold bias you see? the bias appears to evenly spread (figure3) why does this not give a similar spread in ALT estimates (Figure 4) and a related underestimation of ALT?
This is because the shallow ALT sites ($<$ 1.89 m) are mainly in high latitudes (Figrue 5), and in high latitudes the soil temperature was found too warm. This is aligned with Figure 3. In the revision, we changed the caption of Figure 4 to *"The observed sites are mainly located in high latitudes, and the distribution is present in Figure 5."* *to clarify.*

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The ERA5-Land Soil-Temperature Bias in Permafrost Regions

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Abstract. ERA5-Land (ERA5L) is a reanalysis product derived by running the land component of ERA5 at increased resolution. This study evaluates ~~its~~ ERA5L soil temperature in permafrost regions based on observations and published permafrost products. ~~Soil in~~ We find that ERA5L ~~is predicted too warm~~ overestimates soil temperature in northern Canada and Alaska, but ~~too cold~~ underestimates it in mid-low latitudes, leading to an average bias of -0.08 °C. The warm bias of ERA5L soil is stronger in winter than in other seasons. ~~Diagnosed~~ As calculated from its soil temperature, ERA5L overestimates active-layer thickness and underestimates near-surface (< 1.89 m) permafrost area. This is ~~, in part , due~~ thought to be due in part to the shallow soil column and coarse vertical discretization ~~in the ERA5~~ of the land-surface model and to warmer simulated soil. The soil-temperature bias in permafrost regions correlates well with the bias in air temperature and with maximum snow height. Review of the ERA5L snow ~~scheme~~ parameterization and a simulation example both point to a low bias in ERA5L snow density as a possible cause for ~~warm-biased soil~~ the warm bias in soil temperature. The apparent disagreement of station-based and ~~spatial evaluation of ERA5L~~ areal evaluation techniques highlights challenges in our ability to test permafrost simulation models. While global reanalyses are important drivers for permafrost simulation, we conclude ERA5L soil data is not well suited for ~~directly~~ informing permafrost research ~~decision making. To alleviate~~ and decision making directly. To address this, future soil-temperature products in reanalyses ~~would~~ will require permafrost-specific alterations to ~~the~~ their land-surface models~~used~~.

1 Introduction

Permafrost regions occupy more than one fifth of the exposed land area in the Northern Hemisphere (Gruber, 2012) and are subject to important temperature dependent processes (Cheng and Wu, 2007; Westermann et al., 2009; Schuur et al., 2015; Walvoord and Kurylyk, 2016). ~~As permafrost research~~ Research on permafrost is often impeded by sparse observations ~~, global simulation products can~~ and difficult or costly access to study sites (e.g., **??**). Global simulation products have the potential to be an important source of insight if their suitability can be established. ~~Correspondingly, this study investigates~~ To this end, we investigate the accuracy of soil temperature from the new ERA5-Land (ERA5L) high resolution reanalysis with a focus on permafrost area.

Reanalysis ~~,~~ consists of assimilating a broad range of observations into fully coupled process-based models (land-atmosphere-ocean-sea ice, and often biogeochemical components)~~,~~ . It is a valuable source of data for permafrost science. ~~It has~~ Reanalysis products have been successfully used ~~in analyzing and simulating~~ to analyze and simulate various permafrost phenomena at different scales, such as its spatial distribution (e.g., Cao et al., 2019b; Fiddes et al., 2015; Slater and Lawrence, 2013), thermal state (e.g., Guo and Wang, 2017; Koven et al., 2013), active layer thickness (e.g., Tao et al., 2018; Qin et al., 2017), ground ice loss (e.g., Aas et al., 2019), and carbon release (e.g., Koven et al., 2015)~~at different scales. However, such~~ . These applications are mostly restricted to ~~using atmospheric variables as model forcing. By contrast, soil temperature in reanalysis~~ the use of atmospheric variables to drive models. Reanalysis-derived soil temperature is rarely used directly due to ~~the~~ its coarse spatial resolution (50–150 km) and bias. For example, over the Qinghai–Tibetan Plateau (QTP), Hu et al. (2019); Yang and Zhang (2018) reported that the root mean squared error (RMSE) of daily soil temperature ~~was up to 1.8–5.1°C, and generally the soil temperature~~ from different reanalyses (i.e. ~~ERA5-Interim~~ERA-Interim/Land, MERRA-2, and CFSR) ~~is consistently~~ ranged between 1.8–5.1 °C. This error is most often expressed as a cold bias.

ERA5 is the latest reanalysis ~~of~~ product produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Compared to ERA-Interim, it includes new observations and revised processes, such as surface runoff and snow thermal insulation ~~(European Centre for Medium-Range Weather Forecasts, 2018)~~(Hersbach et al., 2020; European Centre for Medium-Range Weather . Cao et al. (2019a) proposed the suitability of ERA5 meteorological data as forcing for permafrost temperature simulation ~~, and its~~ and Graham et al. (2019) reported the improved performance of ~~atmospheric component~~ ERA5 in high latitudes ~~has been reported (Graham et al., 2019)~~relative to other modern reanalysis products. More recently, ERA5L was released as an improved ~~land component of~~ land-only compliment to ERA5. ~~Particularly, the~~ It incorporates new soil and snow hydrology (Balsamo et al., 2009; Dutra et al., 2010), revised soil thermal conductivity (Peters-Lidard et al., 1998), vegetation seasonality (Boussetta et al., 2013), and bare soil evaporation (Albergel et al., 2012)~~likely make it~~ . These improvements are expected to make ERA5L more accurate for many land applications~~. With~~ ; with a spatial resolution of 0.1°, ERA5L is the first global reanalysis product at an intermediate spatial scale between Earth-system land-surface models (e.g., Melton et al., 2019; Chadburn et al., 2015) and statistical and/or remote sensing-based permafrost products (e.g., Obu et al., 2019; Karjalainen et al., 2019b).

Here, we evaluate the soil temperature of ERA5L in permafrost regions ~~against observations and against~~ using observations and other published permafrost ~~products. Furthermore, we~~ data products. We also investigate temperature bias using statistical analysis and ~~example simulations~~ numerical simulation at a well-instrumented location. The objectives of this study are to (1) assess the accuracy of ERA5L soil temperature in permafrost regions and (2) discuss the usability of ERA5L for permafrost research in light of the revealed bias and its potential causes.

2 Data

2.1 ERA5 and ERA5-Land

ERA5 is the latest generation atmospheric reanalysis produced by ECMWF. Data ~~currently covers~~ are currently available from 1979 onward and ~~is expected to be available starting in 1950.~~ availability from 1950 onward is planned. ERA5 is produced using ~~4D-Var~~ four-dimensional variational data assimilation in ECMWF's Integrated Forecast System~~, with~~ ; it has a horizontal resolution of 0.25° (31 km), a temporal resolution of 1 hour, and a vertical resolution of 137 hybrid sigma model levels. The 37 pressure levels of ERA5 are identical to those of ERA-Interim (Noël et al., 2019). ERA5 assimilates improved input data that better reflects observed changes in climate forcing, as well as many new or reprocessed observations that were not available during the production of ERA-Interim. ~~Different from~~ Unlike other reanalyses, ERA5 ~~additionally provides~~ also includes an estimate of uncertainty based on a ten-member ensemble with a reduced temporal resolution of 3 hours and a spatial resolution of 0.5°(Albergel et al., 2018).

The new ERA5L ~~is based on running~~ product is created by forcing the land component of the model ~~driven by, but without coupling to,~~ with the atmospheric models but without coupling them. It uses the Tiled ECMWF Scheme for Surface Exchanges over Land with a revised land-surface hydrology ~~(HTESSEL, CY45R1)~~(HTESSEL, CY45R1, Hersbach et al., 2020). ERA5L is forced by the atmospheric analysis of ERA5 and hence the assimilated observations indirectly influence the simulations. It is delivered at the same temporal resolution as ERA5 and with a higher spatial resolution of 0.1°. ERA5L is currently available for ~~2001–2018, and it will eventually be extended~~ period 1981–2018, and will eventually extend back to 1950 and be updated to the present time with little delay. Note that at the time of writing, only ERA5L data after 2001 have been released to the public and so this evaluation is conducted using data between 2001–2018.

2.2 HTESSEL

2.2.1 Snow scheme

~~Compared to ERA-Interim, a~~ A more realistic representation of snow is used in ~~HTESSEL. It is treated~~ the ERA5 land surface model compared with its predecessor, ERA-Interim. ERA5L uses HTESSEL which treats snow as a single layer above the soil with independent prognostic temperature, mass, density, and albedo (Orsolini et al., 2019). The description of snow processes in HTESSEL ~~by Dutra et al. (2010) can be summarized~~ is summarized by Dutra et al. (2010) as: (1) liquid water with phase changes coexists with ice in the snow pack and is diagnosed from its temperature, mass, and density (Appendix B1); (2) ~~density changes with~~ snow density changes according to overburden, thermal ~~metamorphsim~~ metamorphism and retained liquid water following Lynch-Stieglitz (1994) (Appendix B1); (3) albedo changes exponentially with snow age and is adjusted by vegetation ~~condition~~conditions; (4) snow cover fraction depends on both snow water equivalent (SWE) and density (Appendix B2).

2.2.2 Soil scheme

~~The soil heat transfer of~~ Soil heat transfer in ERA5L is governed by the Fourier law. ~~While the~~ The thermal effects associated with latent heat are accounted for ~~following Rouse (1984)~~by following the method of Rouse (1984). However, soil thermal conductivity depends only on moisture content~~only~~, and the influence of phase change is not represented. The upper boundary ~~is~~ condition is given by a heat flux at the ground surface, derived from a weighted average over eight subgrid fractions (or "tiles"). ~~Zero heat flow~~ A zero heat flux is assumed at the lower boundary. The ~~soil column of ERA5L~~ ERA5L soil column is discretized into four layers with node depths (layer boundaries) ~~of~~ at 0.07 (0–0.07), 0.21 (0.07–0.28), 0.72 (0.28–1.00), and 1.89 (1.00–2.89) m.

2.3 Observations and quality control

Soil ~~temperatures~~ temperature time series from 639 ~~stations~~ sites located in permafrost regions ~~are used~~ were compiled from a variety of sources (Table 1, Figure A1. See station metadata from supplement). ~~These~~ Sites consist of both meteorological stations and boreholes. Of these, there are 56 ~~stations~~ from the China Meteorological Administration (CMA, Wang et al., 2015), 105 ~~stations~~ from World Data Centers (WDC) in Russia and Ukraine, 219 ~~stations~~ from Nordicana D, 95 ~~stations~~ from the Geophysical Institute, University of Alaska Fairbanks (GI-UAF), 10 ~~stations from~~ from the Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) (Su et al., 2011), 60 ~~stations~~ from multiscale Soil Moisture and Temperature Monitoring Network in the Central Tibetan Plateau (CTP-SMTMN) (Yang et al., 2013), 40 ~~stations~~ from the Global Terrestrial Network for Permafrost (GTN-P, Biskaborn et al., 2015), 28 ~~stations~~ from National Park Services (NPS) in Alaska (Wang et al., 2018), 16 ~~stations~~ from the U.S. Geological Survey (USGS, Urban and Clow, 2017; Wang et al., 2018), 8 ~~stations~~ from HiWATER (Che et al., 2019), and 2 ~~stations~~ from Boike et al. (2018, 2019). The ~~site permafrost zone information is derived from~~ permafrost zone of each site was determined based on its location using the digitized Circum-Arctic Map of Permafrost and Ground-Ice Conditions (~~denoted as~~ hereafter referred to as the IPA map, ~~Zhang et al., 2000~~Brown et al., 1997). The observed mean daily soil temperature of these stations ranges from -42 to 38 °C ~~with the elevation range of about 0–5500 m. Additional evaluation with~~ and the elevation of the sites ranges from 0 to 5500 m. An additional 931 stations in non-permafrost regions ~~is conducted~~ were also used for comparison. All the temperature time series ~~are visually checked in order~~ were visually checked to remove obvious ~~outliers.~~ out-of-range values. The mean annual temperature was calculated for sites with data completeness greater than > 95%. Observed active-layer ~~thickness~~ thicknesses (ALT) ~~from Peng et al. (2018) are used~~were obtained from Peng et al. (2018).

2.4 Existing permafrost maps

Four permafrost maps ~~are used here to compare permafrost area diagnosed~~ were used as benchmarks to evaluate permafrost area derived from ERA5L soil ~~temperature~~temperatures. They are (1) the IPA map~~compiled~~ , which is based on observations and mean annual air temperature (MAAT); (2) the heuristic 1-km global zonation index map from Gruber (2012) (~~denoted as~~ hereafter referred to as the PZI map)~~,~~ ; (3) the 1-km Northern Hemisphere permafrost map (Obu et al., 2019) which is based on the semi-physical Temperature at the Top Of ~~the Permafrost table~~ Permafrost (TTOP) model (TTOP map) driven by Moderate Resolution Imaging ~~Spectroradiometers~~ Spectroradiometer (MODIS) land surface temperature ~~,~~ that filled by

Table 1. Summary of soil temperature observations in permafrost regions, including: ~~station~~ the total number of stations (N)~~in permafrost regions~~, the temporal ~~and temperature~~ coverage ~~,~~ and ~~covered~~ range of temperatures (Coverage), the corresponding ERA5L soil ~~layer~~ layers and depth range in metres (SL), and a reference for each dataset, where available.~~)~~

Source	N	Coverage	SL (depth)	Reference
CMA	56	2001–2006 (-26–38)	1–4 (0.05–1.60)	Wang et al. 2015
WDC	105	2001–2015 (-40–30)	2–4 (0.02–1.60)	–
Nordicana D	219	2001–2018 (-42–25)	1–4 (0.00–2.10)	–
GI-UAF	95	2001–2018 (-40–23)	1–4 (0.01–2.00)	Wang et al. 2018
Tibet-OBS	10	2008–2016 (-18–28)	1–3 (0.05–0.40)	Su et al. 2011
CTP-SMTMN	60	2010–2016 (-15–20)	1–3 (0.04–0.40)	Yang et al. 2013
GTN-P	40	2001–2018 (-41–26)	1–4 (0.00-2.40)	Biskaborn et al. 2015
NPS	28	2004–2016 (-33–24)	2–3 (0.20–0.75)	Wang et al. 2018
USGS	16	2001–2015 (-31–25)	1–2 (0.05–0.20)	Urban and Clow2017
HiWATER	8	2012–2017 (-19–22)	~~1–3~~ 1–4 (0.04–2.00)	Che et al. 2019
Others	2	2001–2018 (-32–14)	1–4 (0.04–1.95)	Boike et al. 2018; 2019

downscaled ERA-Interim air temperature; and (4) the 1-km circumpolar permafrost map (CP map) which is derived from a statistical model (Karjalainen et al., 2019a). ~~While~~

Whereas ERA5L, TTOP and CP maps represent permafrost ~~distribution with binary information~~ as a boolean variable (i.e. ~~presence or absence based on~~ present or absent according to soil temperature), the IPA map and PZI map ~~use categories~~ represent permafrost using either a categorical variable (e.g., continuous, discontinuous, sporadic, ~~and~~ or isolated permafrost) or a continuous index (0.01–1) ~~to~~ as a proxy to approximately represent the proportion of an area underlain by permafrost (i.e the permafrost extent). ~~By following Melton et al. (2019),~~ Following Melton et al. (2019), we apply a threshold of 50% (corresponding to the continuous and discontinuous permafrost zones) and 0.5 for the IPA map and ~~0.5 for~~ the PZI map, respectively, ~~are used for permafrost area estimation and for comparing areaswith binary maps .~~ to allow for meaningful comparison with the other maps. Values greater than this are considered to represent permafrost areas. The mean annual ground temperatures (MAGT) from the TTOP and CP maps were also used to evaluate ERA5L.

3 Method

3.1 Evaluation

~~The observed temperatures are grouped by depth according to the four~~ For the purposes of evaluation, temperature observations were only used from depths between 0 m and 2.89 m, corresponding to the range of the ERA5L soil column. Temperature values were grouped according to their depth into one of the ERA5L soil layers. ~~For the layer with observations from multiple depths~~

When this mapping resulted in multiple depths being assigned to a single soil layer, the one nearest to the ERA5L grid center ~~is selected.~~ was selected. The ERA5L soil ~~temperature is~~ temperatures were nearest-neighbour interpolated to ~~observed~~ each of the observation sites to avoid ~~the missing values of adjacent water body~~missing values caused by adjacent water bodies. The mean bias (BIAS), mean absolute error (MAE), and RMSE were used ~~for comparison against observations at~~ as metrics to compare observations to ERA5L at the station scale (see appendix A). ~~As multiple sites could be~~ In the case where multiple sites were located in the same ERA5L grid cell, BIAS, MAE, and RMSE ~~are~~ were calculated for each site individually and then aggregated ~~for each unique grid by averaging with equal weights~~ by averaging all stations in each grid cell ~~. In this context, weighted metrics, for example wBIAS, is used for~~ with equal weight. For the evaluation at ERA5L grid scale~~.~~, these aggregate metrics (for example, wBIAS) were used.

MAAT bias and maximum snow depth (SD_{max}) were selected as candidate variables to be assessed as possible predictors of ERA5L ~~temperature bias. SD_{max} is derived~~ soil temperature bias (see Eq. 1). SD_{max} was defined as the median of annual maximum monthly snow depth during the period 2001–2018. ~~Surface~~ The surface offset (SO), which quantifies the influence of surface conditions ~~, e.g.,~~ such as snow and vegetation cover (Smith and Riseborough, 2002), ~~and is derived~~ is defined here as the difference ~~of MAAT and mean annual ground temperature (MAGT) of soil layer 1~~ between MAAT and MAGT of the uppermost soil layer in ERA5L.

ERA5L ALT was derived by linearly interpolating the ERA5L soil temperature-depth profiles. The TTOP and CP map were derived using an equilibrium model, and MAGT is given as an average of the entire period ($MAGT_{avg}$). This corresponds to 2002–2014 for the CP map and 2002–2016 for the TTOP map, without uniform/specific soil depth. To better evaluate, we aggregated all available observed MAGTs during the period by averaging, and then compared against the $MAGT_{avg}$ of these two maps. Note that the performance of CP and TTOP maps may be lower here than reported in the original publications due to the fact that we evaluate them with a different set of observations (different depths, periods and proportion of sites in mountains).

Permafrost in ERA5L ~~permafrost~~ is limited to the ~~"~~near-surface ~~"~~ due to the shallow simulation depth~~, hence~~ ; consequently, only sites with shallow ALT (< 1.89 m) are evaluated here. ~~Near-surface permafrost is diagnosed from~~ The ERA5L ~~soil temperature in two ways~~near-surface permafrost area is evaluated using existing permafrost maps. An ERA5L grid cell is considered to be underlain by permafrost if either of the following conditions are true: (1) ~~if soil at a depth~~ soil temperature in any of the four soil layers has an hourly temperature below 0 °C for two consecutive years ($ERA5L_H$); (2) ~~if~~ the MAGT of the fourth soil layer is below 0 °C for two consecutive years ($ERA5L_A$)~~, it is considered as permafrost~~.

3.2 Detailed permafrost simulation example

~~The~~ Our results show remarkable bias of ERA5L soil temperature in winter that is thought to correlate with snow depth (Figure 2). For this reason, the suitability of ERA5L soil temperature and the effect of ~~snow-density~~ the snow density bias are further investigated ~~with a site specific~~ using a site-specific simulation example at a densely instrumented location near Lac de Gras (LdG), N.W.T., Canada (Figure 1A). This simulation provides an opportunity to evaluate ERA5L soil temperature under different terrain (e.g. vegetation, soil properties) and snow conditions. We used GEOtop 2.0 (Endrizzi et al., 2014), a

Table 2. ~~Comparisons~~ Comparison of ERA5L with observations and published data products for mean annual air temperature (MAAT), mean annual ground temperature (MAGT) ~~for~~ of different ~~depths~~soil layers, and surface offset (SO)~~against observations and published data products~~.

Metrics		Permafrost region				Non-permafrost region			
		wBIAS	wMAE	wRMSE	N (site, grid)	wBIAS	wMAE	wRMSE	N (site, grid)
MAAT		-1.05	1.88	1.93	2208 (268, 242)	-0.65	1.21	1.24	6095 (829, 828)
SO		0.41	1.84	1.94	268 (78, 67)	-0.83	1.10	1.14	2662 (584, 583)
MAGT	SL1	-0.67	3.12	3.17	1144 (262, 173)	-1.74	2.04	2.07	2761 (627, 611)
	SL2	0.03	2.49	2.57	2330 (472, 283)	-1.43	1.73	1.78	5259 (833, 824)
	SL3	-0.32	2.28	2.36	2070 (338, 261)	-1.51	1.77	1.83	4899 (791, 782)
	SL4	-0.67	2.38	2.47	1658 (248, 215)	-1.69	1.92	1.98	4642 (763, 763)
	Overall	-0.08	2.52	2.60	7202 (556, 331)	-1.52	1.83	1.88	17561 (867, 850)
$MAGT_{avg}$	ERA5L	-0.49	2.15	2.93	1626 (242, 209)	-1.47	1.68	2.38	3901 (581, 581)
	CP	-1.29	1.84	2.62		-1.55	1.71	2.32	
	TTOP	-1.91	2.42	3.30		-0.38	1.28	1.94	

N is the total number of observations, annual or as averages over many years. The number of sites and unique grid cells are also shown in parentheses. SL1 through SL4 correspond to individual ERA5L soil layers, while "Overall" represents an average over the entire soil column. The $MAGT_{avg}$ is the average MAGT over the period 2001–2018 for ERA5L, 2000–2014 for the CP map (Karjalainen et al., 2019a), and 2002–2016 for the TTOP map (Obu et al., 2019). MAAT, SO, and MAGT were evaluated for each individual year, while $MAGT_{avg}$ was carried through once for the entire period and are based on sparse data. $MAGT_{avg}$ must be interpreted cautiously, taking into consideration the points outlined in Section 5.2. Permafrost regions are separated based on the IPA map.

process-based numerical model, ~~is used~~ to simulate snow characteristics and soil temperature for ten terrain types ~~from~~ between September 2015 ~~to~~ and August 2017 as described in ~~more~~ detail by Cao et al. (2019a). Snow compaction due to wind effects is considered in 1-D for all terrain types except for the tall shrub site (Pomeroy et al., 1993). The snow-correction factor (SCF) is used to scale modeled snow mass via precipitation. It is used as a lumped variable for representing precipitation bias in the driving reanalysis as well as differences between terrain types that are caused by preferential ~~deposition~~ accumulation and lateral transport by snow drifting. The ERA5 reanalysis and its ten-member ensemble are used as forcing data for the simulation.

4 Results

4.1 Soil temperature

ERA5L MAGT in the four soil layers has an overall wMAE of 2.52 °C and a wRMSE of 2.60 °C (Table 2). Soil temperature is found ~~too high~~ to have a warm bias in western Canada and Alaska but ~~too cold~~ a cold bias in mid-low latitudes ~~,~~ such as the ~~the~~ QTP, leading to a near-zero wBIAS of -0.08 °C (Figure 3). Among the 932 MAGTs from 331 ERA5L grid cells, 20.7%

Table 3. ~~Comparisons~~ Comparison of ERA5L permafrost area (PA) ~~against~~ with previous estimates.

Map	PA [10^6 km^2]	Diagnostic method	Period represented
ERA5L$_H$	5.5–7.6	Subsurface hourly soil temperature $\leqslant$ 0 °C for two consecutive years	2002–2018
ERA5L$_A$	8.8–10.7	Subsurface MAGT $\leqslant$ 0 °C for two consecutive years	2002–2018
TTOP	13.9	Equilibrium state model with MAGT < 0 °C	2000–2016
CP	13.0–17.2	Statistical model with MAGT < 0 °C	2000–2014
PZI	12.9–17~~.7~~.8	Heuristic-empirical model ~~with PZI > 0.5~~	a few decades prior to 1990
IPA	11.8–14.6	Continuous and discontinuous permafrost zones	a few decades prior to 1990

Note that the CP map only represents permafrost distribution north of 30° N (Karjalainen et al., 2019a), the TTOP map represents the permafrost distribution within the Northern Hemisphere (Obu et al., 2019), and the others represent the permafrost area north of 60° S. Permafrost area from the literature is given with their definition in this study.

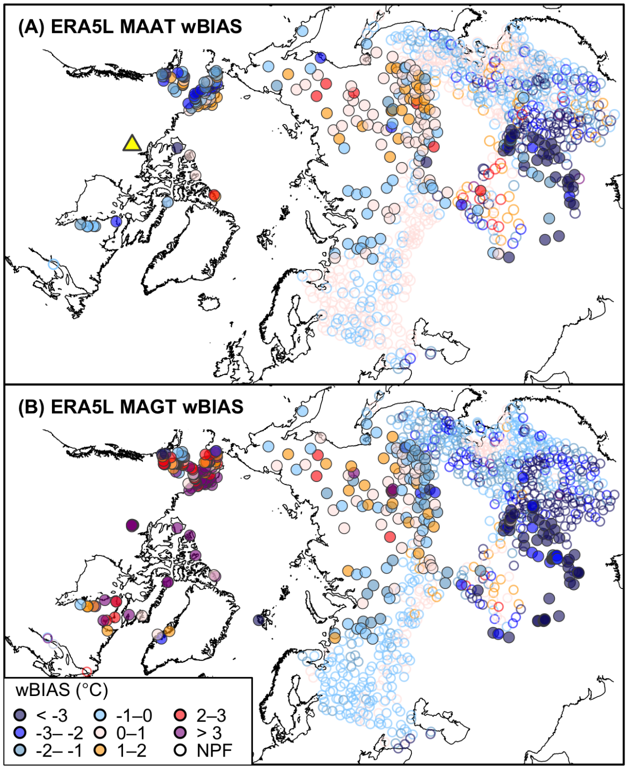

Figure 1. Comparison of ERA5L MAAT (A) and MAGT (B) ~~against~~ with observations. wBIAS is ~~simulated~~ calculated using all available MAGTs from the four soil layers. Filled ~~circle represents~~ circles represent locations underlain by permafrost ~~grids, while~~ and unfilled ~~is the non-permafrost~~ circles represent locations not underlain by permafrost (NPF) ~~one~~based on the IPA map. ~~Lac de Gras is marked as~~ The yellow triangle in (A) marks the location of Lac de Gras, where the detailed permafrost simulation is conducted.

have an RMSE less than 1 °C, 53.5% ~~are better~~ have RMSE less than 2 °C, and 68.9% ~~are better~~ have RMSE less than 3 °C. ~~The linear model is used here~~

The following linear model was used to predict ERA5L soil temperature bias ~~. It is fitted using the 239 grid cells with both MAAT and MAGT leading to the following results~~in permafrost regions using MAAT bias and snow depth as predictor variables:

$$wBIAS = 0.76wBIAS_{MAAT} + 0.77wSD_{max} + 0.15 \qquad (1)$$

where $wBIAS_{MAAT}$ is the weighted bias of MAAT. ~~This model~~ The model was fit using 239 grid cells and has an R^2 of 0.47. Both predictors were found to be statistically significant with $p < 0.01$~~for both predictors~~. The result ~~indicates both~~ suggests that MAAT and snow depth ~~have important influences on~~ both influence ERA5L soil temperature~~: (1) an~~. An increase of 1 °C in MAAT wBIAS corresponds to an increase of 0.76 °C in ERA5L MAGT wBIAS ~~; and (2)~~ and an increase of 1 m in ~~snow depth is equal~~ wSD_{max} corresponds to an increase of 0.77 °C in wBIAS. The overall wRMSE of SO is 1.94 °C and wBIAS is 0.21 °C~~ which is found comparable to that of~~. These results are comparable to those obtained for the land surface scheme (JULES) of ~~UK Earth system model~~ the UK Earth System Model (UKESM) (Chadburn et al., 2015).

Averaged MAGTs from the CP and TTOP map ~~are bilinerly~~ were bilineарly interpolated to the observed sites and compared against the observations of the deepest soil layer. ~~Note~~ We found that the performance of ~~CP and TTOP maps may be lower here than reported in the original publications due to differing observations (depths, periods and proportion of sites in mountains) used. It is found that~~ ERA5L ~~has an intermediate performance compared to them~~is intermediate between the two maps (Table 2). ~~While Karjalainen et al. (2019b) found similar performance~~ Whereas Karjalainen et al. (2019b) found that the predictive accuracy of their statistical model ~~in predicting MAGT in~~ was similar between permafrost and non-permafrost regions, our results show ERA5L and TTOP soil temperature ~~have less agreement~~ agree less with observations in permafrost regions than in non-peramfrost regions (Table 2, Figure 3). In addition to the worse performance of MAAT in these regions, the result suggests that HTESSEL may be less suitable for soil temperature simulation in areas with more prevalent snow and soil freezing~~may reduce the suitability of HTESSEL for soil temperature simulation~~. The large warm bias of ERA5L soil temperature during winter (Figure 2) further supports this notion.

4.2 Active-layer thickness and permafrost distribution

While ERA5L ~~does not have the representation of~~ is not capable of representing deep ALT, our results show that even ~~at the~~ for shallow ALT grids, the mean ERA5L ALT (1.67 m) was more than ~~2 times of observed~~ twice the mean observed ALT (0.82 m) (Figure 4). ERA5L ALT is substantially overestimated for most (72/79) of the grids, with wRMSE values up to 0.98 m. Excluding glaciers, the mean near-surface permafrost area of the Northern Hemisphere ~~is~~ was estimated as 6.6±0.6×10^6 km^2 based on hourly soil temperature and 9.9±0.5×10^6 km^2 based on MAGT during 2002–2018 (Table 2, Figure ~~??~~5). ERA5L underestimates permafrost area compared to ~~earlier~~ previous estimations (e.g., ~~Zhang et al., 2000; Gruber, 2012; Obu et al., 2019; Karjalainen et al.,~~ Brown et al., 1997; Gruber, 2012; Obu et al., 2019; Karjalainen et al., 2019b). Near-surface permafrost area of ERA5L ~~decreased with~~ as defined in this study decreased at a rate of -0.11 (-0.08) $\times 10^6$ km^2 year^{-1} based on hourly (~~annually) soil temperature~~

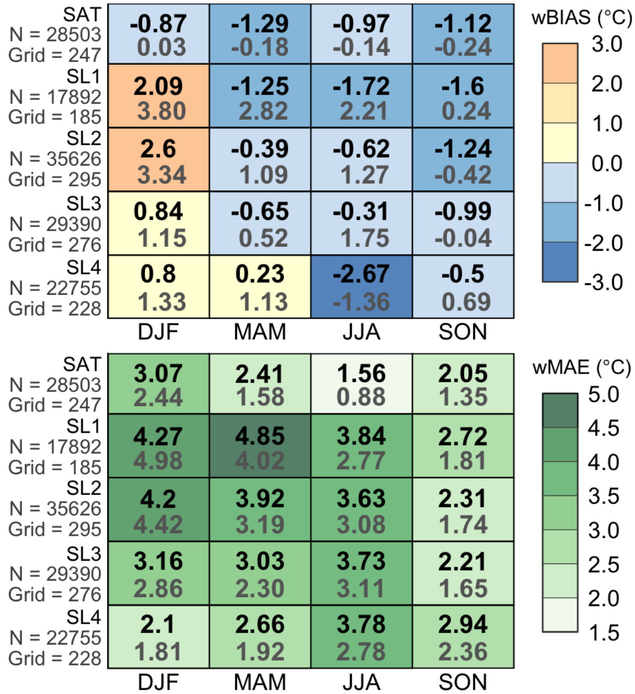

Figure 2. Monthly deviations of ERA5L soil temperature over permafrost regions. Monthly soil temperature is first simulated for each depth and grid, and then the comparison is conducted for each season by averaging the MAE of all grids. ~~The results~~ Numbers in black at the top of each cell are for all permafrost regions. Numbers at the bottom of each cell in grey are limited to results from Russia and Alaska ~~is shown (in gray) in order~~ to ~~compare~~ permit comparison with the results of Melton et al. (2019). SAT is the near-surface air temperature.

~~(Figure ??)~~annual) mean soil temperature. This corresponds to a loss of 1.7 (1.4) $\times 10^6$ km^2 of near-surface permafrost area since 2002. ~~Changes of near-surface permafrost area between 2002–2018 derived from hourly (ERA5L$_H$) and annually (ERA5L$_A$) ERA5L soil temperature. Linear lines represent the trend of permafrost area based on linear model, and the rate is given in brackets.~~

4.3 Detailed permafrost simulation example

The detailed example simulation indicates that ERA5L soil temperature has warm bias (from 0.95 to 5.48 °C) in all terrain types, ~~while~~ whereas GEOtop forced by ERA5 and its ten ensemble members show more reasonable results even when SCF = 1 (Figure 6). ~~Specially, ERAL5 is found to only~~ More specifically, ERA5L was only found to be suitable in terrain types with ~~exceptional~~ significant snow deposition, (e.g. in snowdrifts, tall shrubs, and sedge fen~~, and significantly warm-biased for the~~). For all other terrain types~~during winter, andtherefore, ,~~ ERA5L showed a significant warm bias during winter and, consequently, in the annual mean. ~~While~~ Although the ERA5L ~~SWE agrees with that of~~ results for SWE agreed with GEOtop when driven

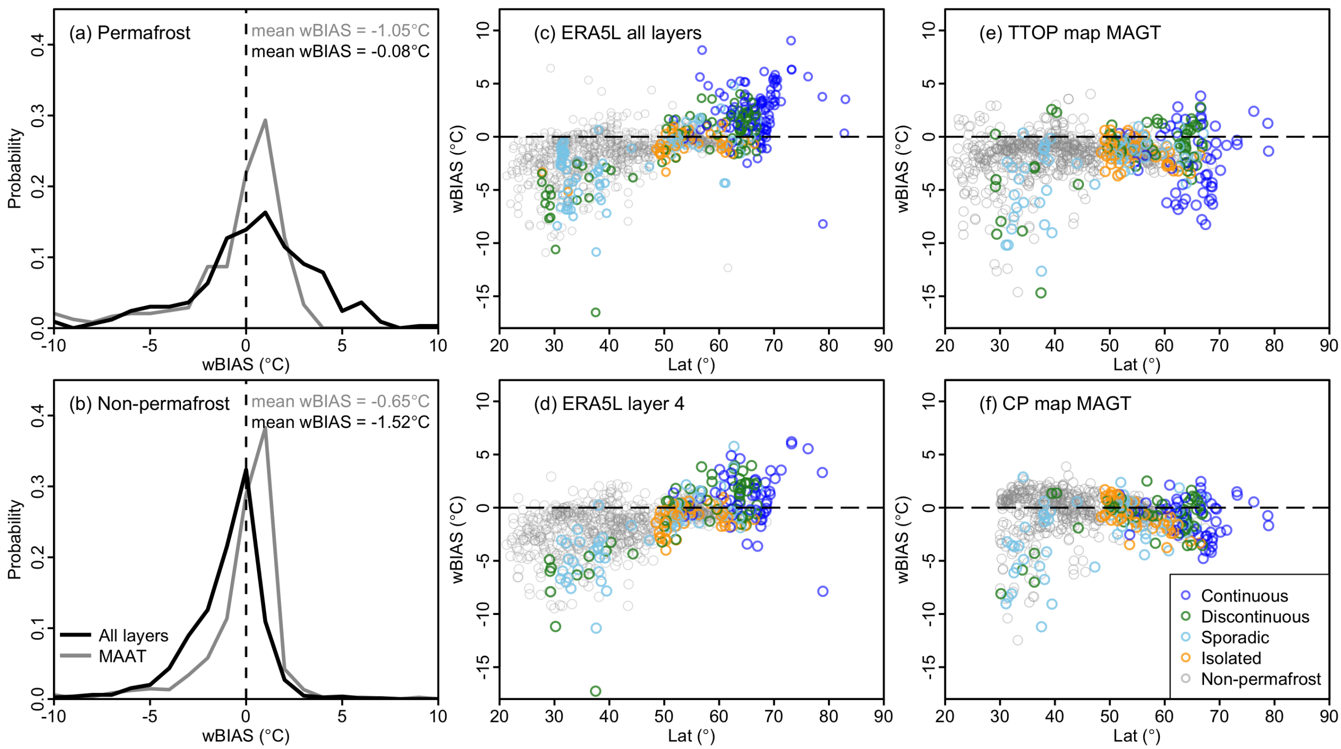

Figure 3. (a & b) wBIAS (~~observation-ERAL~~observation-ERA5L) density of ERA5L mean annual air temperature (MAAT) and mean annual ground temperature (MAGT) in permafrost (a) and non-permafrost (b) regions as a whole. (c-f) wBIAS of ERA5L overall MAGT (c), the last layer (d), TTOP map MAGT (e) and CP map MAGT (f) grouped by permafrost zone.

Table 4. Comparisons of September to March average snow water equivalent (SWE, m), depth (m), and density (kg m^{-3}) near Lac de Gras ~~in~~ for ERA5L and ~~simulated with~~ a GEOtop simulation driven by ERA5.

Model	SWE	Depth	Density
ERA5L	0.07	0.40	156
GEOtop	0.07 (0.01–0.1)	0.27 (0.07–0.4)	208 (160–226)

The snow characteristics of GEOtop are derived using SCF = 1. The range in parentheses represents SCFs between 0.30–1.62, depending on the exact value used for each different terrain type in Figure 6.

with the same data (SCF=1), ~~its~~ the mean snow depth ~~is approximate~~ was approximately 1.53 times that of GEOtop and ~~snow density is~~ the snow density was much lower (Table 4).

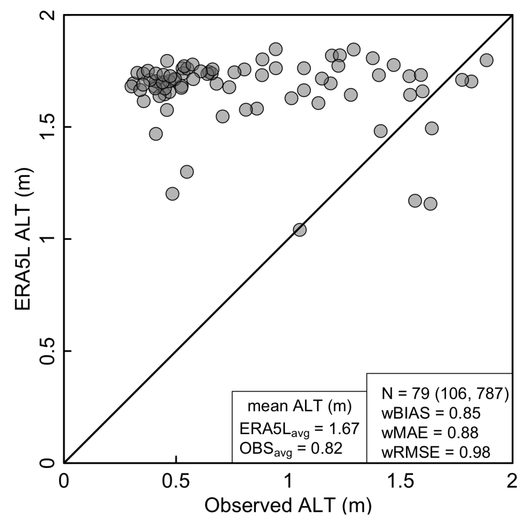

Figure 4. Comparison of ~~shallow~~ active layer ~~thickness~~ thicknesses (ALT) based on 787 measurement from 106 stations located in 79 grids. The observed sites are mainly located in high latitudes, and the distribution is present in Figure 5. The comparison is limited to sites with shallow active layers (< 1.89 m)

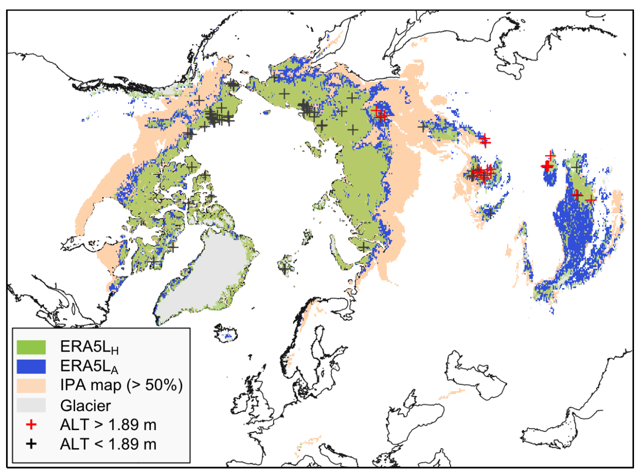

Figure 5. Near-surface permafrost area in 2002 derived from hourly (ERA5L$_H$) and ~~annually~~ annual (ERA5L$_A$) ERA5L soil temperature overlapping the continuous and discontinuous permafrost zones (permafrost extent > 50%) of the IPA map. Active layer ~~thickness~~ thicknesses (ALT) ~~is~~ taken from Peng et al. (2018).

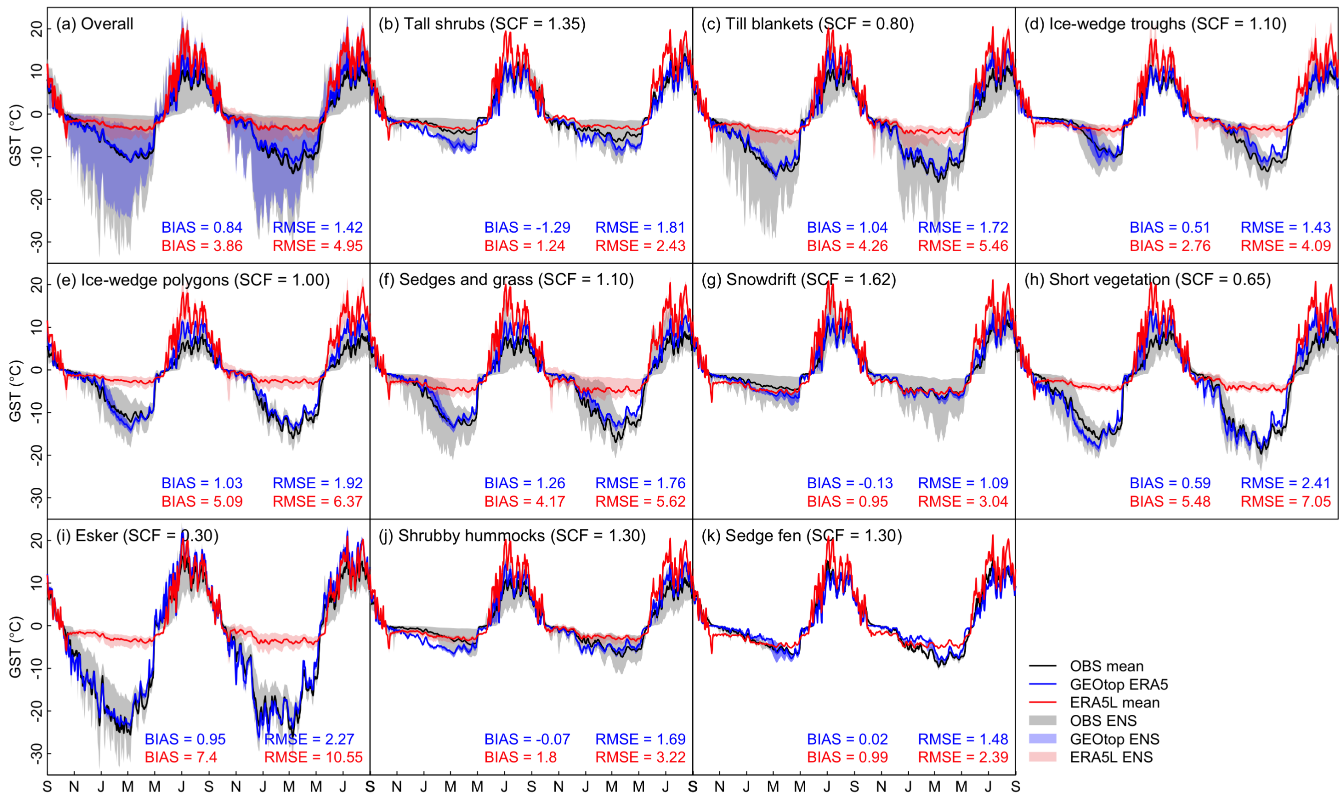

Figure 6. Ground surface temperature (GST) at ~~the depth of~~ 0.1 m depth for ten terrain types with different snow ~~deposition~~ accumulation tendencies in LdG, ~~northern~~ Northern Canada. Observations and GEOtop ERA5 are taken from Cao et al. (2019a) ~~, while the~~ and GEOtop ENS is the ensemble range derived from the ten-member ensemble of ERA5. Note that soil temperatures from the first layer of ERA5L ~~soil temperature~~ are used here. The BIAS and RMSE are simulated at a daily scale for each terrain type.

5 Discussion

5.1 Suitability of ERA5L soil temperature

ERA5L has a number of advantages ~~, such as long-term~~ for permafrost research; it provides a long historical record (back to 1950, eventually), high spatial resolution, and global coverage. While it could be seen to provide an opportunity to study long-term changes of permafrost at an intermediate scale (∼9 km) without additional model simulation, our results indicate that significant bias in ERA5L soil temperature limits its utility for permafrost research.

Compared to ~~the~~ a coarse-grid (∼2.8°) simulation (Figure 4 from Melton et al., 2019), ERA5L often has more reasonable results in ~~the deep soil layeralthough less permafrost processes are coupled, but~~ its deepest soil layer, despite the fact that fewer permafrost-specific physics are included in the HTESSEL. The results of ERA5L are generally worse in the shallow soil layers (Figure 2). ERA5L does not reproduce ALT well (Figure 4), likely due to its shallow soil column, coarse vertical discretization, warm bias in soil temperature and lack of phase-dependent thermal conductivity in soil. Furthermore, ERA5L shows ~~remarkable low bias in estimated~~ a remarkable underestimation of total permafrost area (Table3, Figure 5) when compared with previous estimates. ~~The reason~~ An explanation for this is that the large ALT (i.e. > 1.89 m) that frequently ~~develops~~ develop in mid-latitude mountains (e.g., Zhao et al., 2010; Cao et al., 2017) ~~,~~ cannot be represented by the shallow soil column of ERA5L. While this could ~~result in a low bias~~ contribute to an underestimation of permafrost area on the QTP, where observed ALT is generally large, ~~a cold bias of soil temperature is found here at the same time.~~ we observe a simultaneous cold bias in soil temperature which counteracts the first effect. Our results indicate that the cold bias of ERA5L in mid-low latitudes is highly aligned with the MAAT bias (Figure 1). This is also suggested by the linear model (Eq. 1). On the other hand, ERA5L underestimates permafrost area in Canada and Alaska ~~although~~ despite the observed ALT there ~~is~~ being mostly low. This is because the ERA5L soil temperature in western Canada and Alaska ~~appears~~ is too warm with a wBIAS of about +1.5 °C.

Loss of permafrost is ~~to be expected with~~ an expected consequence of a warming atmosphere. While the loss of near-surface permafrost area derived from ERA5L is similar to ~~that in~~ previous land-surface model simulations (Lawrence et al., 2008; Slater and Lawrence, 2013), the absolute numbers and the rate of loss ~~, however,~~ have little value for further interpretation ~~. This is because~~ because the permafrost area has a pronounced bias to begin with and its temporal dynamics are known to be badly represented with a shallow soil column and are likely ~~subject to~~ affected by an inadequate representation of snow. Furthermore, because permafrost extent is a variable that cannot be observed, we fundamentally lack possibilities for proper validation (Gruber, 2012).

5.2 Model evaluation with sparse data

~~Using~~ Looking exclusively at summary statistics from 242 sites in 209 grid cells ~~alone~~ would misleadingly show that ERA5L ~~to have comparably good skill in representing~~ has a relatively good ability to represent the thermal state of permafrost~~, for exampleoutperforming~~ . For example, consider that ERA5L outperformed the TTOP map in all evaluation metrics (Table 2). ~~Its~~ However, its simulated permafrost area ~~, however,~~ is visibly low when plotted ~~geographically~~ on a map (Figure 5). ~~Both~~ These contradictory findings can be reconciled because of the warm bias at high latitudes and cold bias in mid-latitudes ~~cancel out each other~~ which cancel each other out based on the ~~observations available~~ available observations (Figure 3). Clearly, an improvement in summary statistics alone is not a sufficient criterion of superior model performance. ~~Along these lines, the~~ Notably, the International Permafrost Association action group "Specification of a Permafrost Reference Product in Succession of the IPA Map" ~~of the International Permafrost Association recommended~~ reported in 2016 that, in order to make progress, we needed the capability to measure whether a new map or model output was of superior quality compared with an old one~~and for this,~~ . For this, they recommended that the permafrost community ~~needed to~~ develop and provide the necessary data, methods, and standards (Gruber, 2016).

5.3 Scale effects

Even for ~~an small area that is~~ a small area within a single grid cell of Earth-system models or reanalyses (10–100 km), evaluation with point observations ~~are~~ remains difficult. This ~~could be~~ is demonstrated by our simulation example at LdG~~. Within~~ ; within an area of about 20 km × 30 km, MAGT and SO can vary by almost 7 °C ~~(Cao et al., 2019a)~~ based on plot sizes on the order of 15 m × 15 m (Gruber et al., 2018). This is important ~~in two ways~~for two reasons. First, the results from statistical evaluations of ~~a~~ coarse-scale products such as ERA5L ~~significantly depend~~ depend significantly on the local selection of observation sites. This issue is ~~know~~ known as the spatial effect when the lack of spatially-distributed measurements consistent with the size of model grid cells (i.e. 0.1° in ERA5L) is a potential source of error for model evaluation (Gupta et al., 2006; Gubler et al., 2011). Second, ERA5L ground temperatures can ~~at best only represent~~ only represent at best a small fraction of the area within each ~~of its grid cells and, as a consequence,~~ individual grid cell. Consequently, their value as part of a permafrost climate ~~service for informing ,~~ services system for informing local decision making (e.g. ~~, local decision making for adaptation~~for adaptation), is limited.

5.4 Snow densification and heat transfer

The seasonal ERA5L soil temperature deviance (Figure 2A) and linear model (Eq.1) show a remarkable bias toward high soil temperature in winter ~~,~~ that is correlated with snow height. While we do not imply that ~~GEOtop-based~~ the GEOtop simulations are correct or ~~representing~~ accurately represent metamorphism in Arctic snow ~~accurately~~ (see Domine et al., 2019), they do demonstrate that simulations with snow cover of similar mass but different density are able to match ground-temperature observations far better than ERA5L. Since snow thermal conductivity ~~is described as a exponential formulation~~ can be described as an exponential function of its density (Eq. B12), the low-biased snow density of HTESSEL would contribute to a much lower snow thermal conductivity. ~~Furthermore, with~~ With the same SWE, ~~low-biased snow density means high-biased~~ a low bias in snow density implies a high bias in snow depth. In this context, the temperature gradient, and hence the heat flux though the snow pack~~are then smaller~~, are both reduced. Using the mean snow density in Table 4 as an example, a snow density of 75% would reduce ground heat-loss though the winter to about 44%. Even though this ~~is~~ represents only one local case study at LdG, it sheds light on ~~what may be causing the bias revealed for~~ a possible cause of the ERA5L soil temperature bias in cold regions more broadly. Interestingly, HTESSEL and GEOtop both use the same exponential formulation of snow thermal metamorphism proposed by Anderson (1976) but with different parameters. HTESSEL uses a value of 460 ($m^3\ kg^{-1}$) for c_ξ ~~(Dutra et al., 2010),~~ , a parameter controlling change in snow density due to thermal metamorphism (Eq. B5) (Dutra et al., 2010). This value is 10^4 times ~~of that~~ greater than the value for c_ξ in GEOtop (Endrizzi et al., 2014) and Anderson (1976). ~~As a consequence, with snow density greater than 100~~ Consequently, for snow densities greater than 150 kg m^{-3}, ~~its~~ the change rate (s^{-1}) related to thermal metamorphism remains near zero in HTESSEL. While this may explain, at least in part, the bias in ERA5L snow density and soil temperature, it is unknown whether the excessively high value for HTESSEL is merely an error in the publication cited or whether it reflects the value in the code. An additional contribution of GEOtop to higher snow densities in tundra environments may be the effect of blowing snow (cf, Pomeroy et al., 1993).

5.5 Implications

While global reanalyses provide urgently needed meteorological drivers for permafrost simulation, their soil data is not well suited for directly informing permafrost research or local adaptation decisions. As such, simulations using permafrost-specific land-surface models driven by reanalyses (Cao et al., 2019a; Fiddes et al., 2015) will likely be increasingly important in the provision of permafrost climate services. Making future soil-temperature products like ERA5L directly usable will require significant permafrost-specific alterations in model design, especially with respect to snow cover and the total depth of the ground representation for the land-surface models that are used. If indeed the value of the parameter c_ξ in the snow metamorphism of HTESSL is in error, then this would be an easy improvement.

6 Conclusion

Our results support five conclusions.

1 ERA5L soil temperature has a warm-bias at high-latitude and a cold bias in ~~mid/~~mid- to low-latitude, high-elevation areas. The soil-temperature bias in permafrost regions correlates with bias in air temperature and with maximum snow height. Seasonally, soil temperatures in winter are more strongly warm biased than in other seasons. With more prevalent snow and ice, ERA5L soil ~~temperature matches~~ temperatures match observations less well in permafrost-affected regions than in non-permafrost conditions.

2 Permafrost area is strongly underestimated when derived from ERA5L soil temperature and its temporal trend cannot be interpreted with confidence due to the bias in absolute area as well as model limitations.

3 Active-layer thickness is overestimated when derived from ERA5L soil temperature. This is due to the warm-bias in simulations as well as the shallow soil column and coarse vertical discretization used.

4 ERA5L snow density is hypothesized to have a low bias, at least in high-latitude areas, explaining part of the warm bias in soil temperature.

5 Summary statistics ~~of~~ comparing ERA5L with other spatial permafrost data based on their skill in reproducing observations do not agree with a geographic comparison of permafrost zones that are known to exist with some (albeit difficult to quantify) confidence. Whereas ERA5L performs well in the statistical evaluation, it severely underestimates permafrost area, especially in Canada and Alaska. This highlights the remaining challenges in developing data and procedures for testing permafrost simulation models and products.

~~While global reanalyses provide urgently needed meteorological drivers for permafrost simulation, their soil data is not well suited for directly informing permafrost research or local adaptation decisions. As such, simulations using permafrost-specific land-surface models driven by reanalyses (Cao et al., 2019a; Fiddes et al., 2015) will likely gain importance. Making future soil-temperature products like ERA5L directly usable will require significant permafrost-specific alterations to the land-surface models used.~~

Code availability. The Python script for downloading ERA5-Land is developed from API request provided by ECMWF Climate Data Store (CDS) service and is available from the supplement.

Data availability. Soil temperature over China is not publicly available but could be requested from National Meteorological Information Center (http://data.cma.cn/). The other datasets are open access (last access: 5 November 2019). WDC dataset is available from http://www.wdcb.ru/, GTN-P dataset is available from https://gtnp.arcticportal.org/, USGS dataset is available from https://pubs.er.usgs.gov/publication/ds1021, NPS is available from https://irma.nps.gov/DataStore/, HiWATER dataset is from the Cold and Arid Regions Science Data Center at Lanzhou (https://doi.org/10.3972/hiwater.001.2019.db), Tibet-Obs and CTP-SMTMN is available from National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/zh-hans/data/ef949bb0-26d4-4cb6-acc2-3385413b91ee/). The Nordcana D data is available from http://www.cen.ulaval.ca/nordicanad/en_index.aspx, GI-UAF is available from Permafrost Laboratory of University of Alaska (https://permafrost.gi.alaska.edu/content/data-and-maps), and the datasets from Julia Boike is available from https://doi.pangaea.de/10.1594/PANGAEA.880120 and https://doi.pangaea.de/10.1594/PANGAEA.905236. The PZI and TTOP maps are available from their publication, and the IPA map is available from National Snow & Ice Data Center (https://nsidc.org/data/GGD318/versions/2).

Appendix A: Evaluation metrics

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(T_{obs} - T_{mod}) \tag{A1}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}(|T_{obs} - T_{mod}|) \tag{A2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(T_{obs} - T_{mod})^2}{N}} \tag{A3}$$

where T_{obs} is observed soil temperature and T_{mod} is the temperature from ERA5-Land soil temperature, GEOtop, or literature.

Appendix B: Snow scheme of HTESSEL

B1 Snow densification

Snow density ρ_s (km m^{-3}) is constrained to be between 50–450 kg^{-3}. The compaction of snow density, or change rate (s^{-1}), is parametrized as

$$\frac{1}{\rho_s}\frac{\partial \rho_s}{\partial t} = \frac{W_S}{\eta} + \xi_s + \frac{\partial L_s}{\partial t}\frac{1}{SWE - L_s} \tag{B1}$$

where the first term represents overburden, second term is thermal metamorphism (Anderson, 1976; Boone and Etchevers, 2001), and the last term is the influences of snow liquid water (L$_s$, kg m^{-2}) following Lynch-Stieglitz (1994). W_s (Pa) is the pressure of overlying snow mass or snow water equivalent (SWE, m) , and η (Pa s^{-1}) is the viscosity coefficient of snow.

$$W_S = \frac{1}{2} \cdot SWE \cdot g \tag{B2}$$

where g is the acceleration of gravity of 9.807 (~~ms~~m s^{-2}). Snow viscosity is described as a function of snow temperature (T$_s$, K) and density following Anderson (1976)

$$\eta = \eta_0 \cdot \exp(a_\eta \cdot T_D + b_\eta \cdot \rho_s) \tag{B3}$$

where η_0 = 3.7 × 10^7 (Pa s), a_η = 0.081 (K^{-1}), b_η = 0.018 (m kg^{-3}). T_D (K) is the depression temperature,

$$T_D = 273.16 - T_s \tag{B4}$$

The change rate of ρ_s related to thermal metamorphism is ~~parametrized~~ parameterized as

$$\xi_s = a_\xi \cdot \exp\left(-b_\xi \cdot T_D - c_\xi \cdot \Delta\beta_s\right) \tag{B5}$$

where the a_ξ, b_ξ, and c_ξ ~~, and ρ_ξ~~ are constant values of 2.8×10^{-6} (s^{-1}), 0.042 (–) ~~,~~ and 460 (m^3 kg^{-1}) ~~, and 150 (kg m^{-3})~~ derived or modified from Anderson (1976) and Jordan et al. (1999). $\Delta\beta_s$ (kg m^{-3}) is given as

$$\Delta\beta_s = \begin{cases} 0, & \rho_s \leqslant \rho_\xi \\ \rho_s - \rho_\xi, & elsewhere \end{cases} \tag{B6}$$

where ρ_ξ (kg m^{-3}) is equal to 150 kg m^{-3}. L_s is diagnosed from snow temperature, SWE, and snow density,

$$L_s = f(T_s)\cdot L_s^c \tag{B7}$$

where $f(T_s)$ is the snow temperature function and L_s^c is the snow liquid water capacity (kg m^{-2}).

$$f(T_s) = \begin{cases} 0, & T_s < T_f - 2 \\ 1+\sin\{\frac{\pi(T_s-T_f)}{4}\}, & T_s \geq T_f - 2 \end{cases} \tag{B8}$$

where T_f is 273.16 (K), L_s^c is parameterized as a function of SWE and β_s,

$$L_s^c = SWE\cdot[r_l^{min} + (r_l^{max} - r_l^{min})\cdot C] \tag{B9}$$

where r_l^{min} and r_l^{max} are constant values of 0.03 and 0.1, and C is given as

$$C = \begin{cases} 0, & \beta_s > \beta_s^l \\ \frac{\beta_s^l - \beta_s}{\beta_s^l}, & \beta_s \leq \beta_s^l \end{cases} \tag{B10}$$

where β_s^l is 200 (kg m^{-3}).

B2 Snow cover fraction

Snow cover fraction (SCF) can be given as

$$SCF = \frac{1}{SD_{cr}}\frac{SWE}{\rho_s} \tag{B11}$$

where SD_{cr}, the minimum snow depth that ensures complete coverage of the grid box, is set as 0.1 m.

B3 Snow thermal conductivity

By following Douville et al. (1995), the snow thermal conductivity (λ_s) is treated as a function of snow density,

$$\lambda_s = \lambda_i(\frac{\rho_s}{\rho_i})^{1.88} \tag{B12}$$

where λ_i is ice thermal conductivity of 2.2 (W m^{-1} K^{-1}) and ρ_i is ice density of 920 (kg m^{-3}).

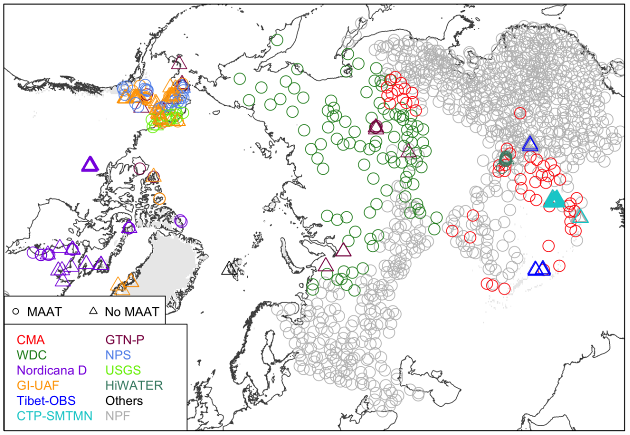

Figure A1. Distribution of soil temperature stations. Stations in permafrost regions are in color while the gray ones are non-permafrost (NPF) stations.Stations in circle have additional air temperature observations; stations marked by a triangle do not.

Author contributions. BC carried out this study by analyzing data, performing the simulations, organizing as well as writing the manuscript and was responsible for the compilation and quality control of the observations. SG proposed the initial idea, and contributed to organizing as well as writing the manuscript. XL and DHZ contributed to the writing the paper.

Competing interests. The authors declare that they have no competing interests.

Disclaimer. The authors declare that they have no conflict of interest.

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