Response to reviewers

Dr. Francisco José Cuesta-Valero on behalf of all coauthors

2023-03-17

Dear Editor,

We thank the anonymous reviewer for the thorough and constructive feedback. This file provides a complete documentation of the changes made in response to each of the reviewer's comments. Reviewer's comments are shown in normal text, including the number associated with the reviewer and the number of the comment. Author's responses are shown in blue, bold, italic text. Indicated line numbers correspond to the version of the manuscript with changes marked unless otherwise indicated.

Reviewer 1

The detailed response to the review comments is very much appreciated. A number of improvements have been made to the manuscript and for the most part, any comments I had have been adequately addressed. I have suggested a few minor revisions which are either editorial or to improve clarity.

Minor comments:

Reviewer's Comment 1.1 — L31 – As mentioned in comment on original MS, Obu (2021) provides an equilibrium estimate of permafrost extent (i.e. uses TTOP model). Permafrost that exists due to past climate change including that in the southern portions of the permafrost region are likely underestimated. I still think that you should be clear that this is an equilibrium estimate based on current climate conditions.

Authors' Response: ***We have modified the text accordingly (line 31).***

Reviewer's Comment 1.2 — L32-33 – Although it is good that you have added the range considered for these permafrost temperature changes, it only represents a specific decade. You could consider longer-term rates which are updated each year in the state-of-climate reports published in BAMS (most recent Smith et al. 2022), or use the rates reported in Ch 2 of IPCC AR6 WG1 report (Gulev et al. 2021). This would make it clearer to the reader that this warming of permafrost has been going on for several decades and is continuing.

Authors' Response: ***We have modified the manuscript accordingly (line 34).***

Reviewer's Comment 1.3 — L-34-37 – Although there have been revisions made to indicate that these estimates only consider "near-surface" permafrost extent, you should also be clear that this refers to 2-3 m depth. A better way to present estimates of permafrost loss would be to give it as a volume as is done in Burke et al. 2020 (and also in the IPCC rept – Fox-Kemper et al. 2021). Estimates are given for volume of permafrost loss per degree of warming which

is probably a more effective way of describing impact of warming on permafrost (less ambiguous and lower chance of misinterpretation than “near-surface permafrost extent”).

Authors’ Response: ***The reviewer is right, permafrost volume is less ambiguous than permafrost extent. Nevertheless, permafrost extent is a well-known metric in the community, thus we are now reporting both the changes in permafrost extent and volume (lines 37-38).***

Reviewer’s Comment 1.4 — L37-38 – Be clear here that the latent heat uptake is required for phase change of the ice in permafrost.

Authors’ Response: ***We have modified the text accordingly (line 40).***

Reviewer’s Comment 1.5 — L135 – Check date of Brown et al. The map was published in 1997 as indicated by the citation for the map. This date should probably be given rather than date of access for the digital version.Brown J, Ferrians Jr. OJ, Heginbottom JA, Melnikov ES (1997) Circum-Arctic map of permafrost and ground-ice conditions. U.S. Department of the Interior, U.S. Geological Survey, Map CP-45.

Authors’ Response: ***Done.***

Reviewer’s Comment 1.6 — L131-135 – Does this variation in ice content with depth, take into account that higher ice contents (especially for segregated ice) are usually found near the permafrost table. Some clarification would help.

Authors’ Response: ***For the consideration of excess ice, we relied only on the information provided by the ground ice map of Brown et al. (1997), i.e., we increased the ground ice content in the upper*** 10-20 m ***by an amount according to the classification into low/medium/high excess ice content given in the map. As the map by Brown et al. does not provide more detailed information on the vertical distribution of the excess ice, we assumed a uniform distribution of excess ice with depth within that part of the ground. We have also modified the manuscript in order to improve the clarity of this point (lines 136-139).***

Reviewer’s Comment 1.7 — L229-L233 – It might be useful to look at the air temperature data for the region around Hudson Bay and northeastern Canada. My recollection is that there was recent cooling into the 1990s then followed by a period of warming. Spatial variation in temporal change in air temperature may explain some of the patterns regarding heat storage gains. Rouse (1991) might be useful in explaining spatial patterns in heat storage around Hudson Bay.

Authors’ Response:

As suggested, we have checked the surface temperature evolution around the Hudson Bay in the CRU TS 4.05, HadCRU 4, and GISSTEMP 4 products (Figure R1). Indeed, all three products display a cooling during the 1990s as indicated by the reviewer (top of the figure). Nevertheless, the magnitude of the cooling is not enough to explain the heat loss in the water bodies of the region, as air temperature trends indicate a long-term warming during the period of interest (i.e., 1960-2020, bottom of the figure).

Therefore, this analysis does not explain the negative heat storage in inland water bodies around the Hudson Bay, requiring a more elaborated analysis that could be completed in future iterations of this work.

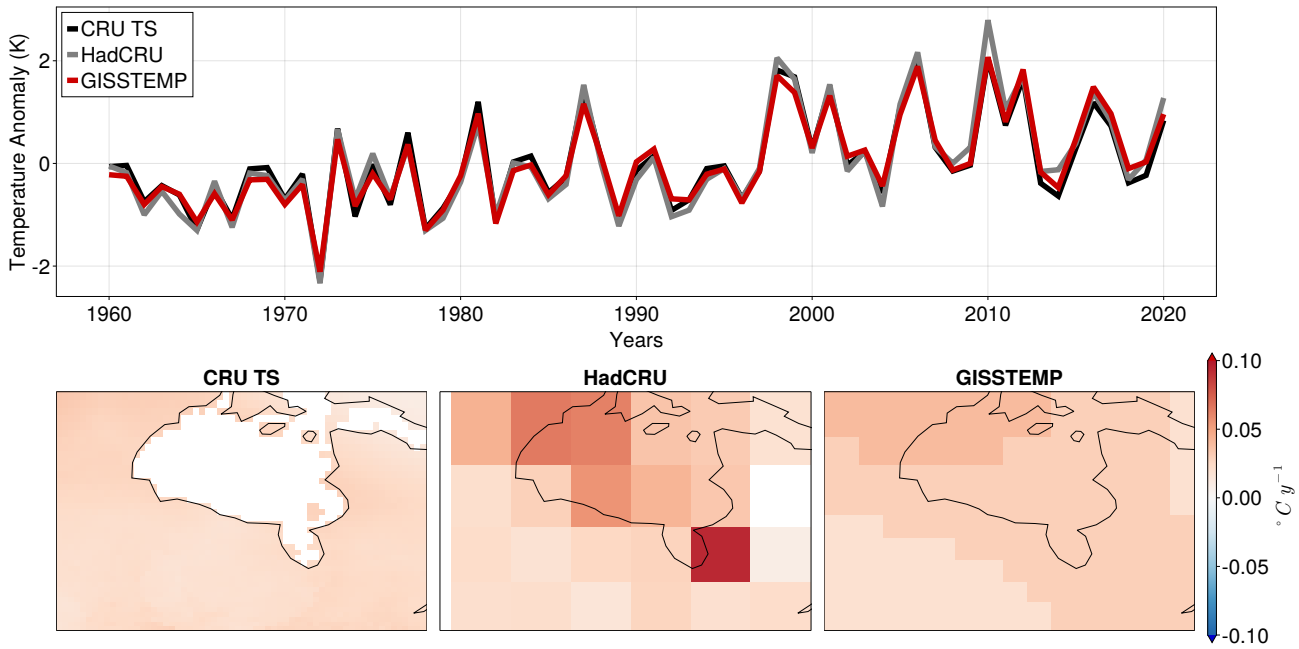

Figure R1: (top) Surface air temperature anomalies relative to 1960-2020 for the southwestern shore of the Hudson Bay within CRU TS 4.05 data (black), HadCRU 4 data (gray), and GISSTEMP 4 data (red). (bottom) Trends of surface air temperatures during 1960-2020 for the same products.

Reviewer's Comment 1.8 — L298 – Rather than referring to "abrupt thaw of ground ice" (or ice-rich permafrost), it would be more informative to mention that it is really the changes in the landscape associated with permafrost degradation that exacerbate or enhance the rate of thaw as they do result in a change to the boundary condition by removing material and can also result in increased importance of lateral heat flow (e.g. pond formation and associated collapse of material around pond). Including something on landscape process is important as this really is the "abrupt" part.

Authors' Response: ***The manuscript has been modified accordingly (line 301).***

Reviewer's Comment 1.9 — L303 – There can be changes to both water quantity and quality with respect to freshwater conditions. The increased in groundwater flow (and baseflow) will also result in increased mobility of dissolved material that had been immobile in permafrost. This will be important for fish habitat as well as drinking water sources.

Authors' Response: ***We have specifically mentioned the presence of dissolved materials in frozen water in the new version of the manuscript (line 306).***

Reviewer's Comment 1.10 — L307-308 – Revision suggested for clarification: "...due to thermokarst processes including ground subsidence, ponding of water, slope instability, riverbank instability and channel widening." (thermokarst processes refer essentially to thawing and settlement of ice-rich permafrost so that the examples given are due to thermokarst processes).

Authors' Response: ***Thank you for the suggestion, we have incorporated it in the manuscript (lines 312-313).***

Reviewer's Comment 1.11 — L309 – It is unclear what is meant by "modify traditional construction ways". There were problems in the past because southern construction methods were used that did not consider permafrost. However, since about the mid-twentieth century the potential thaw of permafrost has been considered in engineering design with techniques such as pile foundations, removal of ice-rich material, thick gravel pads as well as use of passive cooling — see for example the large body of work by NRC building research division. Consideration of climate change is more recent, although this has more or less been done for about 25 years, including development of standards and guidelines. It would be better to say that there may be increased infrastructure maintenance costs due to permafrost thaw or something similar.

Authors' Response: *We have included the suggested changes in the new version of the manuscript (line 314).*

Reviewer's Comment 1.12 — L325 – Some clarification is required and it is suggested that "thawing of permafrost" be used instead of referring to "thawing of subsurface ice". Permafrost consists of soil or rock as well as ice. It is largely the organic matter within the soil material that stores the carbon rather than the ice. While I agree as mentioned above, the melting of the excess ice in the permafrost can result in landscape change that can exacerbate thaw, it is more correct to refer to permafrost rather than the ice when referring to carbon.

Authors' Response: *We have modified the text accordingly (line 330).*

Reviewer's Comment 1.13 — L363-364 – Revision suggested "… represented in the Land Surface Model (LSM) components is.…" – I think this is what you mean.

Authors' Response: *We have incorporated this suggestion in the text (line 367).*

Reviewer's Comment 1.14 — L367 – revise to "…in LSMs have also improved.…" (i.e. LSMs – plural)

Authors' Response: *We have fixed this in the new version of the manuscript (line 371).*

Reviewer's Comment 1.15 — L395-396 – These are borehole temperatures (generally upper 20 to 30 m although some are deeper), rather than surface temperature measurements (although the boreholes are not as deep as the ones used in the determination of ground heat storage in the MS). A revision is therefore required.

Authors' Response: *We have fixed this in the new version of the manuscript (line 399).*

Reviewer's Comment 1.16 — L635 – This paper does not appear to have been accepted and is a "discussion paper" or preprint still undergoing review – maybe indicate it is in review or is a discussion paper?

Authors' Response: *We have fixed this reference in the new version of the text, indicating that it is a preprint.*

Reviewer's Comment 1.17 — Figures 1 and 4 – For clarity revise label to "Permafrost Thaw" so that it is clear that reference is being made to latent heat, rather than the sensible heat considered for "Ground" component in figures.

Authors' Response: ***We have modified the figures accordingly.***

References

Gulev SK, Thorne PW, et al. (2021) Changing State of the Climate System. In: Masson-Delmotte V, Zhai P, Pirani A et al. (eds) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 287-422. doi:10.1017/9781009157896.004

Rouse WR (1991) Impacts of Hudson Bay on the terrestrial climate of the Hudson Bay Lowlands. Arctic and Alpine Research 23:24-30

Smith SL, Romanovsky VE, Isaksen K, Nyland KE, Kholodov AL, Shiklomanov NI, Streletskiy DA, Drozdov DS, Malkova GV, Christiansen HH (2022) [Arctic] Permafrost [in "State of the Climate in 2021"]. Bulletin of the American Meteorological Society 103 (8): S286-S290. doi:10.1175/BAMS-D-22-0082.1

References

Brown, J., Ferrians, O., Heginbottom, J., and Melnikov, E. (1997). *Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2*. National Snow and Ice Data Center. National Snow and Ice Data Center [Last accessed: 2023-03-10]. DOI: 10.7265/skbg-kf16.