Dear Reviewer,

We thank you for your thorough and constructive feedback. This file provides a complete documentation of the changes made in response to each of your comments. Reviewer's comments are shown in normal text, author responses are shown in bold, italic, blue text.

Reviewer 1

General Comments

The manuscript submitted by Cuesta-Valero et al. considers continental heat storage and determines the contribution from three components. The analysis is important as it contributes to better understanding of the overall global heat balance by ensuring that all components are accounted for in the calculation of continental heat storage. The subject area is therefore appropriate for publication in ESD and would be of interest to its readers. The MS is also relevant to better estimates of the impact of climate change on the landmass. The MS has clear objectives and is generally well written with results and interpretations presented clearly. I don't have any major concerns with the MS but I do have a number of comments that should be considered prior to acceptance for publication.

One of the key things that is done in the paper is the calculation of the heat in the ground that is utilized for phase change (latent heat) as ice in permafrost melts. However, the way the paper is written the authors seem to consider this separate from the subsurface (or ground) heat storage, which I found odd. Permafrost is a component of the ground (essentially a thermal condition of the ground) in cold environments so both the heat used to raise its temperature or for phase change when it thaws are components of the heat that is stored in the ground. It would seem that this is more an issue of the method that has been traditionally utilized to determine ground heat storage. Analysis utilizing subsurface temperature profiles only considers conduction in the estimate of ground heat fluxes. As ground temperatures approach 0 °C in permafrost, heat is utilized for phase change of any ice in the ground rather than raising the temperature and little change in temperature over time is observed in ground temperature profiles (as discussed in Romanovksy et al. 2010; Smith et al. 2010). Lack of consideration of the latent heat effects therefore means that ground heat storage determined considering only conduction would be underestimated. It would make more sense for the authors to say that they are refining the estimates of ground heat storage by addressing a limitation of the method traditionally used by considering the latent heat utilized for phase change in the estimates.

The reviewer is right that permafrost is just perennially frozen ground and that our permafrost heat storage estimate is essentially the change in latent heat storage. Furthermore, available methods to estimate ground heat storage from subsurface temperature profiles cannot include latent heat flux used to thaw permafrost, as indicated by the reviewer.

In our analysis, we use a model and a series of assumptions about the stratigraphies of the Arctic subsurface in order to estimate the latent heat used in permafrost thawing, in order to complement the observation-based method used to derive sensible ground heat storage. That is, we separate the sensible and latent heat fluxes, mainly due to methodological limitations. Therefore, we believe that it is better if we maintain both estimates of heat storage as separate entities in order to improve the clarity of the manuscript.

We have added a couple of lines in the new version of the manuscript to make clear the division into sensible and latent heat fluxes.

The authors do not mention the role of other modes of heat flux in the ground such as convection. Heat transfer associated with water movement (advection) such as infiltration of precipitation and snow melt or subsurface water flow may also influence the ground thermal regime (see for eg. Douglas et al. 2020; Neumann et al. 2019; Phillips et al. 2016; review of Smith et al. 2022b also discusses this). As permafrost thawing occurs, subsurface water flow becomes more important. Is lack of consideration of this mechanism of heat flow also a limitation of the method used to determine ground heat storage?

Indeed, our approach to derive estimates of permafrost heat storage is not able to include an active hydrology in the subsurface. We have noted this fact as a limitation in the manuscript.

Regarding advection in subsurface temperature profiles, the diameter of the drilling holes is usually small enough to prevent air advection. Water advection is still possible, which may introduce a non-climatic signal in the profiles. Nevertheless, all logs were screened by eye, and those including signals that cannot be explained by climate alone were removed (see the details in Cuesta-Valero et al., 2021).

We have added a couple of lines in the new version of the manuscript clarifying this point.

I have a number of additional comments (see below) for the authors' consideration in preparing the revised manuscript. These comments identify where further clarification or information may be required. Suggestions for editorial revisions have also been provided.

Specific comments (keyed to line number)

L31 – See comment above – permafrost is the ground (earth material) so its thaw is a component of subsurface heat storage.

We have already addressed this comment above.

L32 – Suggested revision: “ The ground accounts for 90

Done.

L41 – What is included in “cryosphere”? Permafrost is a component of the cryosphere but it is treated separately in this paper.

In this context, the term cryosphere refers to glaciers and ice caps. We have indicated this in the new version of the manuscript.

L53 – Permafrost includes soil and rock. Since there can be water within rock, phase change can also occur in frozen rock (even if the amount is small compared to soils).

We have changed the text to reflect this point.

L55 – replace “underline” with “underlie”

Done.

L55 – Note Obu (2021) determines the equilibrium permafrost distribution so it does not consider permafrost that formed under a colder climate and still persists today. For example, permafrost in peatlands in the southern portion of the permafrost regions formed under colder conditions and is preserved due to the insulating properties of peat. Also, permafrost can be quite thick in the Arctic and it can take a century or more to completely thaw so that relict permafrost continues to exist as climate warms.

This is correct. We wanted to give an idea of the total area underlain by permafrost. Please note that the reported warming for permafrost after the Obu (2021) reference corresponds to recent times.

L56 – It is important to note that these are average values of warming based on several sites (I believe Biskaborn 2019 gives a range).

We have added the uncertainty ranges to the new version of the manuscript.

L59 – Misleading/incorrect statement. These simulations only consider the upper 2-3m of permafrost rather than its total vertical extent, which may be 10s to 100s m. These values therefore do not refer to complete loss of permafrost from this area (i.e. refer to thaw being more than 2-3m over this area).

CMIP simulations from Koven et al. (2013), Slater et al. (2013) and Burke et al. (2020) consider only shallow permafrost. Nevertheless, the LSMs considered in Hermoso de Mendoza et al. (2020) and in Steinert et al. (2021) consider soil columns with hundreds of meters of depth. However, we agree with the reviewer that the range of change in global permafrost extension refers to shallow permafrost, thus we have changed this in the new version of the paper.

L61 – Permafrost is frozen ground so permafrost heat uptake is ground heat uptake. Until it thaws, the heat storage would be accounted for by the methods (inversion of temperature profiles) utilized to determine ground heat storage.

We completely agree with the reviewer. Because of this, we refer only to the change in the area of permafrost in the previous line, and not to the change in permafrost temperature.

L66 – What is meant by recent times? It would be clearer to give the time period over which this reduction occurred.

We meant the last three decades. We have included this period on the text.

L67 – suggested revision: ‘ . . . .going to continue throughout the 21st century. . . :

Done.

L79 – should this be “deep subsurface temperature profiles”

Done.

L87 – replace “in” with “of”

Done.

L89 – revise to “slope of this regression line” (or best-fit line)

Done.

L99-100 – If the time for temperature changes at the surface to reach a given depth depends on the thermal properties, how does truncating to the same depth yield the same temporal reference if thermal properties are variable?

The reviewer is right, the time required for a surface perturbation to reach a certain depth depends on thermal properties. What we are assuming to provide the temporal reference indicated in line 101 is an homogeneous subsurface with a thermal diffusivity of $1.0 \times 10^{-6}\ \mathrm{m^2\,s^{-1}}$*, which is a typical value for bedrock. We have modified the text to clarify this point.*

L131-134 – I may have missed something here - how are the results from point-based measurements applied to the entire area considered. In figure 2a, heat storage is shown for points that are not uniformly distributed with very large areas not represented. It isn't clear how the point-based data are extrapolated to the larger area or what other information may be utilized especially give the large areas with no data.

We followed the methodology in Cuesta-Valero et al. (2021), consisting in obtaining the averaged heat flux from all 1079 subsurface temperature profiles, and then estimating the accumulated heat considering a global land surface of $1.34 \times 10^{14}\ \mathrm{m^2}$*. That is, we consider the area of all continents excluding Antarctica and Greenland, since we have no measurements there. This is possible because previous works have shown that the current distribution of boreholes is enough to capture global changes in surface conditions (e.g., Pollack et al., 2004; García-García et al., 2016). Furthermore, Cuesta-Valero et al. (2021) showed that changing the area considered does not affect the global estimates.*

We have changed this paragraph in the new version of the manuscript to enhance the clarity of the text.

L136 – Isn't it more correct to say that the heat input to the subsurface is utilized to melt ground ice as permafrost temperatures approaches 0 °C?

Indeed, that is the complete physical process: permafrost thaws once the ground temperature is near zero Celsius degrees and the heat keeps getting into the ground. We have added a couple of lines in the text to explain the entire process.

L140 – Do you mean the surface offset which is the difference between mean annual air and ground surface temperatures and is influenced by snow cover. The thermal offset refers to the difference in temperature between the ground surface and the top of permafrost, which (if equilibrium conditions exist) depends on difference between frozen and unfrozen thermal conductivity (See for e.g. Riseborough et al. 2008).

We fully agree with the reviewer and changed the formulation accordingly.

L143 – What about rock – permafrost includes rock which can contain ice.

We used the dataset by Pelletier et al. (2016) to set the soil thickness and assumed bedrock underneath. The water/ice content in the bedrock was reduced compared to the overlying soil. Both parameters (soil thickness and bedrock ice content) were varied during the ensemble simulations to address the related uncertainties. Please see Langer et al. (2022) for details.

L179 – How is depth determined?

The lake depth is given by the Global Lake Database v.3(Choulga et al., 2019), as indicated in line 176 of the original manuscript.

L165-199 – Lakes can form or drain in the Arctic due to permafrost thaw. Is the change in surface water distribution due to thermokarst processes considered or is this a limitation to heat storage estimates?

Unfortunately, the permafrost model used here cannot represent thermokarst processes nor water redistribution. We detailed those limitations in line 341 of the original manuscript. Furthermore, we did not consider dynamic (thermokarst) lake changes in the inland water heat storage which relied on a static lake distribution. We would like to note that the overall trend of thermokarst lake dynamics is very uncertain since both lake expansion and drainage happen concurrently. For the study period of the past few decades, the net lake area change is likely negligible compared to the total lake area.

L220 (also elsewhere in paper including L223) – See earlier comments. Permafrost heat flux, if thaw is not is not occurring (this will be the case where temperature below melting point of ice in the ground) will be considered in the estimates of subsurface storage determined utilizing subsurface temperature records. It is only when thaw occurs in warmer permafrost at temperatures near 0 °C that latent heat needs to be considered in addition to conduction.

Please, see comment about L136 above. We only consider permafrost heat flux as latent heat flux. Permafrost warming is only considered from subsurface temperature profiles. We have added a clarification in Section 2.2.

L235 – Where around Hudson Bay? There was cooling in the eastern Arctic including northern Quebec into the 1990s – is this the reason for the lack of heat gain in this area?

Indeed, there is a decrease in inland waters heat storage in the southwestern shore of the Hudson Bay. (Figure 2 of the original manuscript). Unfortunately, we are unable to explain this result, and we found no explanation in the literature either. We have reported this issue in the new version of the manuscript.

L267 – Why isn’t the Tibetan Plateau included given it is a fairly significant area. Permafrost in this region is generally warm so latent heat effects are important.

Indeed, the Tibetan Plateau is an important region that should be included in the analysis. However, the simulated permafrost relied on an input dataset of soil organic carbon (Hugelius et al., 2014) which is only available for the northern permafrost region excluding the Tibetan plateau. It is planned to include the Tibetan Plateau in the next iteration of this analysis, as indicated in the manuscript.

L275-276 – It is important to indicate here that the estimate of ground heat flux needs to consider non conductive heat flow (i.e. address limitations) to improve estimates. The MS makes progress in addressing this limitation by considering the latent heat associated with phase change as permafrost thaws.

We think that advection is not significant for ground heat flux at the global scale. For example, Huang (2006) uses meteorological observations of surface air temperature (SAT) to derive the evolution of global ground heat flux, reaching similar results to those in (Beltrami, 2002) from subsurface temperature profiles (GST). If nonconductive processes were relevant at the global scale, these two estimates should be different, as SAT observations would not account for these additional processes. We find that this result indicates that heat transport by conduction is the leading mode of heat diffusion trough the subsurface, with the exception of permafrost soils where thawing/freezing is occurring. Furthermore, Xibalbá profiles were screened to remove logs including advection (Cuesta-Valero et al., 2021), as indicated in the manuscript.

L280-300 – This section is OK but most of this has been well covered in other publications so nothing really new here.

Indeed, this part of the text is based on previous publications. Our aim was to reflect the most important results related to permafrost heat storage in order to provide a picture of the impacts that permafrost thawing posses for society and ecosystems. We have added also a small comparison with other components of the cryosphere in the new version of the manuscript in order to place our estimate in the context of the global ice budget.

L280-285 –Other implications of ground warming and permafrost thaw are impacts on landscape processes and stability, changes to surface water distribution and increase in subsurface water flow. These impacts can also have feedbacks to the ground thermal regime with further impacts on carbon feedback.

We have added these points in Section 4 of the new version of the manuscript.

L288-290 – This is really an issue of landscape change associated with thawing of ice-rich permafrost (such as subsidence, thaw slumps), which is abrupt or sudden, exacerbating permafrost thaw – with geomorphic change such as slumps and other slope failures the upper boundary changes as material is removed (also lateral heat flow).

Please, see the added text to answer the previous comment.

L293 – Do you mean “surpassing” rather than “trespassing”

Yes, we meant “surpassing”. This is now fixed on the text.

L295-300 – Other impacts related to permafrost thaw (especially if ice-rich) include loss of bearing strength and ground settlement/subsidence with impacts on infrastructure; landscape instability including slope failures which can release sediment into water bodies with implications for water quality; impacts on integrity of contaminant containment facilities.

Please check Section 4 in the new version of the manuscript, we have noted those points in there.

L301-303 – more evaporation?

Indeed, global lakes have experienced larger evaporation rates in recent decades. Nevertheless, the leading factors causing this evaporation increase seem to be ice cover reductions (Wang et al., 2018; Zhao et al., 2022). However, for low latitude lakes, evaporation could increase by the process that lake surface temperatures warm at a slower rate than the overlying air, which leaves more energy from long-wave radiation available for lake evaporation (Wang et al., 2018). We have indicated this in the new version of the text.

L325-335 – There are several recent ground temperature records in the permafrost regions (some results included in Smith et al. 2022b, Noetzli et al. 2022, Biskaborn et al. 2019 and other papers). These are generally at shallower depths (usually upper 20 m) than would be utilized for the inversion of ground temperature profiles that is utilized in the MS. However, these provide information at depths where latent heat effects are important.

We are aware of those ground temperature measurements, and we are planing to include them in a future iteration of this analysis. We have added some lines in the new version of the manuscript to clarify this point.

L337 – This is not a new observation and the lack of ground ice information has been identified as a limitation in permafrost modelling in other papers (e.g. Smith et al. 2022b; O’Neill et al. 2020).

Yes, this is not a new result. However, this is an important limitation affecting our results, thus we think that an explanation must be included in the text for completeness and transparency.

L347 – With respect to latent heat effects related to permafrost thaw, including the Tibetan Plateau is probably more important than permafrost zones of Antarctica given the rather dry conditions and the geology.

Correct, and because of that we plan to include the Tibetan Plateau as soon as computational and financial resources are available, moving towards achieving global coverage in a later iteration.

L358-359 – While the deeper subsurface is an improvement, the LSMs still have limitations with respect to representation of subsurface conditions including ground ice distribution.

Indeed, the lack of accurate data about the distribution of ground ice affects model development, as well as other research fields. But beyond ice representation, the depth of the LSM also affects subsurface thermodynamics, and in this regard the expansion of the LSMs' depth has improved the simulated permafrost in global climate models (e.g., Nicolsky et al., 2007).

L382 – As mentioned in previous comment there are borehole temperature measurements in permafrost and at some sites, there are moisture content measurements. There are also often observations of excess ice content when boreholes are drilled.

Indeed, sometimes you can have some borehole sites with more complete measurements. But the problem is that those extended measurements are seldom available, and that their number is very reduced. Therefore, those sites are very probably not representing global conditions, nor have them a sufficient temporal coverage to include decadal changes in temperature. Such limitations make them, therefore, unsuitable for the scope of our analysis.

L385 – One of the issues in areas such as the Canadian Arctic is the remoteness and significant cost of drilling boreholes, especially deeper ones where specialized equipment needs to be transported to the site (see for e.g. Smith et al. 2022b). Most permafrost monitoring sites therefore are often located near communities, existing infrastructure, associated with resource development (hydrocarbon, mining) etc.

Exactly, permafrost monitoring is a complex task because of the difficulty for maintaining the sites and covering such a vast extension of land. We have included this point in the new version of the manuscript.

L392 – This is also discussed in Smith et al. (2022b) and O'Neill et al. (2020). There are also efforts to improve ground ice potential modelling and mapping – see for e.g. O'Neill et al. (2019)

We have included this point in the new version of the manuscript.

Figure 5 – See previous comments regarding other implications of permafrost thaw such as impacts on infrastructure integrity. Landscape instability is a more inclusive term than ground subsidence.

We have replaced ground subsidence for landscape instability in Figure 5.

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