Dear Dr. Lei Cai et al.,

Thank you for your responses to the Author's Comments. I recommend that you submit a revised manuscript according to address the referee's comments and few more that I have made that stem from their comments.

Re: Referee #2

Referee #2 seems generally satisfied with the revised version of the manuscript, but offers a few major points and several minor points that you have indicated will be addressed in your next revision. Your replies seem to address the questions adequately, with the exception of the reply to R2's comment about your assumption on Line 220:

"Line 220: "Have the same area fraction of low ice landunit", You may add "(20%)" to make it clearer. What is the reason behind this assumption?"

Please make the reason behind this assumption clear in the revised version of the manuscript. I do not fully understand the logic as written in your Author's Reply.

Authors' reply: We have elaborated on the assumption in the revised manuscript.

Re: Referee #1

Referee #1 was not that satisfied with the revised version of the manuscript, and did not provide comments on the Results and Discussion as a consequence. R1's major criticisms still stem from initial concerns raised in the first round of reviews that there was (i) not enough demonstration of the empirical basis for the parameterization of excess ice, and (ii) that knowledge and understanding gained from empirical ground ice studies needs to be made clearer to the reader. R1 provided several detailed points to help crystalize the issues.

Having read through your Author's Reply to R1, I have the following suggestions for you to incorporate into your next revision:

As you say you intend to, please ensure that you state early on a clear scope and what the great limitations are.

Authors' reply: We have clarified the scope and limitations of this study (model development) in both the introduction and discussion sections in the revised manuscript.

Regarding terminology around ground ice content, I hope that it is made clear in the revised version. In the Author's Reply you say "we emphasize that volumetric ice content in this study refers only to excess ice bodies", but this is not how most readers think of volumetric ice content. Volumetric ice content is pore ice + excess ice. If you use the term "volumetric excess ice", it must always mean the volume ice in excess of the pore ice. The terminology must be reconciled, made clear to the reader, and agree with how the terms are commonly defined.

Authors' reply: We have now refined the terminology throughout the manuscript. Now we have changed the "volumetric ice content" to "volumetric content of excess ice" or "volumetric excess ice content" in order to emphasize that the ice content we refer to is only for the excess ice bodies that exceed the soil pore space. For the volumetric content of ground ice that includes both excess ice and pore ice, we keep using the term "volumetric content of total ground ice" or "total volumetric ice content" for clarification. One exception is that the ice content of the CAPS data, for which we keep using "volumetric ice content" to keep the terminology consistent with the source data. As suggested by the R1, in the

revised manuscript we clarify that the "volumetric ice content" is approximately equal to the "volumetric content of excess ice" in our study because the production of CAPS data is mostly based on the visible excess ice bodies (Heginbottom et al. 1995).

Regarding excess ice content outside of the Yedoma Region, I suggest that you try to follow R1's comment and develop a way to better initialize wedge ice types that are not within Yedoma deposits. R1 makes a good suggestion to "overlay CAPS and Yedoma areas in a GIS and examine the overlap within chf, chr, and dhf to better inform and substantiate landunit parameterizations/area weights", which should be follow up on in the revised manuscript. Perhaps also have a look at O'Neill et al. (The Cryosphere, 13, 753–773, 2019, https://doi.org/10.5194/tc-13-753-2019).

Authors' reply: We agree that the reviewer has given constructive suggestions on the initialization of high ice landunit, while we did not follow his advice for several reasons. One reason we have mentioned in the reply to R1 that this new scenario on high ice landunit does not decrease the uncertainty of excess ice initialization on the global scale. There is also a technical issue for the current version of our model development that it does not support freely configuring excess ice volumetric contents for landunits in different grid points, which means that all the high ice landunits in the same domain have to have the same excess ice cryostratigraphy. Making it possible to initialize different cryostratigraphies for the same excess ice landunit but in different locations needs substantial changes in the source code and surface data variables, which probably should be regarded as a new version. Since all model development work needs several updates since the release of the first version, we have planned to add the function of freely configuring excess ice stratigraphy for each grid point/landunit in the upcoming version, which is also dependent on the new excess ice datasets. We have added text in the discussion section about the limitations and potential improvements of our current model development on excess ice initialization scenario and excess ice landunits assignments.

In your response to R1's comment 3, you state a caveat about the availability of ground ice information helpful to your sub-grid representation:

"As we mentioned, there is a lack of dataset on ground excess ice with enough information helpful for our sub-grid excess ice representation. For this reason, this is our best effort to make a possible scenario of excess ice distribution based on the best dataset (the CAPS data) at this time, even though it only provides generalized information and has been released for more than 20 years. Due to the lack of adequate information in excess ice distributions, the purpose of this study is not to make an accurate estimate of excess ice melt and surface subsidence in the 21st century, but rather to develop a functionable process within a land surface model on a global scale. Once there is a new generation of excess ice dataset, the CLM with sub-grid excess ice representation is able to be operational and give more accurate projections of excess ice melt and surface subsidences."

Please make sure that you state something to this effect in the introduction. Stating the clear purpose will set up clear expectations from the reader. This caveat should also be echoed in the Discussion. Given all of the uncertainty, and the goal of making a functioning process within the land surface model, it would be instructive to include a sensitivity analysis of the effects of differing sub-grid excess ice representation.

Authors' reply: We have added stuff about the scope and limitations of this model development study in both the introduction and discussion. We keep our idealized simulation

and analysis of the sensitivity of different sub-grid distribution of excess ice (North Slope of Alaska and Yakutsk) in the previous version of manuscript (tc-2019-230) and put it into the supplemental material.

Regarding R1's point 4, I don't follow the calculation in your example. If the original soil layer is 7.5 m thick (between 1 and 8.5 m), and you increase it's volume by 70%, 7.5 x 1.70 is 12.75. adding back the first 1 m of ground gives 13.75 m of hydrologically active soil, no? Not sure how one arrives at 18.5 m of hydrologically active soil. In any case, please make sure that the added content in the main text makes the model design clearer.

Authors' reply: In the example taken in the reply to R1, since the soil layer after adding excess ice has the volumetric content of excess ice of 70%, the original soil layer takes 30% of the volume. In this way, the new thickness of soil is calculated as $1+7.5\times0.7\div0.3=18.5$ (m).

Regarding R1's point 5, it perhaps stems from the initial set up of the reader's expectations. You have indicated that you have added clarification in the new text to address this point. I additionally suggest that if the purpose of the manuscript is "not to retrieve realistic excess ice melt, but rather to compare the model results from this study and from Westermann et al. (2016)", then this purpose needs to be stated explicitly, and the inclusion of comparisons to empirical studies should be carefully done so as not to give the wrong impression.

Authors' reply: We have added clarification in this section that the single-point experiments over the Lena River Delta are just for model evaluation so that we want to initialize excess ice exactly the same as in Westermann et al. (2016) in order to compare the model results in the two studies.

Regarding R1's point 6, I agree that the schematic should show how the model actually represents ground ice in the grid point. Show the "squeezing". If the added ice is "evenly distributed within each soil layer", please show this distribution. It is expected that this representation is an abstraction, and not reality.

Authors' reply: After some discussion, we decided to remove the upper left panel of figure 3 to avoid misunderstandings. We think that the upper right part of figure 3 has already presented the concept of "squeezing". We have also added text in the methodology section about "squeezing" to make our statement clear.

Please note the references kindly provided by R1 and incorporate where appropriate.

Authors' reply: We have incorporated the references provided by R1.

I look forward to receiving your revised manuscript in the near future.

Best regards,

Peter

Anonymous Referee #1 Received and published: 1 June 2020 This is a resubmission of a previous discussion paper that was retracted by the authors following review: https://www.the-cryosphere-discuss.net/tc-2019-230/. For context, my previous review is available here: https://doi.org/10.5194/tc-2019-230-RC1.

The single-point modelling has been changed to simulate 3 geomorphic units in the Lena River delta, rather than Yakutsk and the North Slope of Alaska in the initial submission. The global simulations include comparison of a no ice case, sub-grid representation case, and a grid-average case.

My main criticisms of the first submission were that (a) the results were not validated in any meaningful way, (b) the empirical basis for the parameterization of excess ice was lacking, and (c) that there was not a clear comprehension of empirical ground ice studies and knowledge of ground ice conditions.

I have read up to the results section and made several observations pertaining to points (b) and (c) above. The points below do little to reassure me of my concerns with (b) and (c) from the previous version. Furthermore, in my previous review I pointed out that references mentioned in text were missing from the reference list. I expected such a simple item would be remedied, but in the first paragraph of the introduction alone, the following references are missing from the list: Walter et al. (2006); Schaefer et al. (2011).

Given these concerns, I have not formally reviewed the results or discussion.

Authors' reply: We appreciate your valuable comments which have contributed much to this new revision of our manuscript. Here we respond to your two (remaining) main concerns. The individual points have been addressed below.

First of all, we have tried to clarify the scope of the study in the new manuscript, which is to provide a proof-of-concept for how heterogeneous excess ground ice can be represented in a global Land Surface Model (LSM) used in Earth System Models (ESMs). While much work remains before excess ice is represented in a fully satisfactory way in ESMs, we believe this study represents an important step forward compared to the current generation models, which for the most part fully ignores excess ground ice (only representing pore ice). Much development of CLM (and other LSMs) in recent years have aimed at mechanistic representation of key features, even when improvements to the model performance cannot be demonstrated. As an example, the latest version of CLM showed an apparent degradation in representation of snow water equivalent at global scale, despite mechanistic improvements in snow physics (Lawrence et al. 2019). We believe our model enhancement is in line with this aim, as it accounts for the effect of heterogeneous excess ice on hydrology and thermal properties in a physically sound way, even though there are great limitations in the current study, especially related to the initialization of excess ice.

Secondly, we have now clarified the terminology. As you correctly pointed out, the previous version of the manuscript was ambiguous here, which understandably gave concern about the use of observational studies. We want to highlight here again that we fully recognize the limitations in excess ice initiation in our study. The observational studies listed in the manuscript are not intended to be replicated here but are used to motivate the use of three broad excess ice classes, which should be revisited in future studies.

1. It is unclear from the text whether the authors appreciate the difference between “excess ice content”, “volumetric ice content”, and “visible ice content”, as the terms are seemingly used interchangeably or confused.

In different places in the paper, the authors have indicated the CAPS values represent volumetric ice content, excess ice content, and visible ice content. The authors have misinterpreted the legend for the Circum-Arctic Map of Permafrost (CAPS) in their Figure 2. They have altered the legend from the original map by removing the clause stating “visible ice in the upper. . .”, and now only indicate “Ground Ice Content: percent by volume”. They report ice contents from the Circum-Arctic Map as volumetric ice content (lines 216, 224) in the text. Then, in the figure 2 caption, they suggest the CAPS values represent the “Spatial distribution of excess ground ice” – very confusing. The CAPS legend, and the Permafrost Map of Canada (Heginbottom et al. 1995) legend on which the CAPS compilation is based, both clearly indicate that the ice content reported is the visible ice content (as the authors correctly indicate on line 177). The legend on the Heginbottom et al. (1995) map indicates this visible ice percentage accounts for “segregated ice, intrusive ice, reticulate ice veins. . .”. The percentages on the maps do not correspond to volumetric ice content (in the strict sense), which also include the pore ice fraction.

Lines 185 to 190, the authors report that Yedoma is “characterized by massive ice wedges leading to typical average volumetric ice contents in the range from 60% to 90%” (line 188). They then state: “We therefore set the volumetric excess ice content to 70%”. Nowhere in the text do the authors mention the soil porosity, which is key to estimating excess ice content given only volumetric ice content. For example, if one assumes a soil porosity of 0.5, then volumetric ice contents of 60-90% represent excess ice contents of about 10-40%. Assuming an excess ice content of 70% based on volumetric ice contents of 60-90%, as presented above, is problematic. I refer the authors to Harris et al. (1988) for definitions of volumetric ice content and excess ice content.

Other examples that seemingly use the terms interchangeably: Line 137-138 “volumetric ice contents ranging from 60-80%” and in the next sentence, “higher excess ice contents are found in Pleistocene sediments. . .”; Line 193 “For the low ice landunit, we assume both a significantly lower volumetric ice content and a smaller vertical extent of the excess ice body”; Table 1. The caption reads “excess ice initialization scenario”, but the table header indicates “Volumetric Ice content”. Presumably, porosity is available, so why not also present the readers with excess ice content?

Finally, the term “ice content” (line 198) is also used on its own, as is “Overall Ground ice content” in Table 2, further complicating interpretation by the reader. What type of ice content? I’m left wondering throughout.

Authors’ reply: We agree with the referee’s comments that the terminology about ice content is somewhat unclear throughout the manuscript that could lead to misunderstanding of the main purpose of this study. But we do not believe we misrepresented the physical properties of ground ice overall when incorporating them into the structure of the large scale land surface model. The physical properties of ground ice used in our model development is only for the excess ice bodies that exceed the pore space of soil. In our model development, we do not address pore ice physics because it is already represented in the original CLM model, with the output variable named “soilice”. The melting of “soilice” in the CLM5 does not cause surface

subsidence as this ice only exists as part of pore space. Therefore, we emphasize that volumetric ice content in this study refers only to excess ice bodies. We agree that directly applying the groun ice content in the CAPS data is not necessarily an accurate way, while we have to make sufficiently simple classes of ice content levels to avoid over-parameterization. We think that using the volumetric ice content provided by the CAPS data is generally valid for the purpose of this research since the CAPS data is based mostly on "visible" ice bodies (Heginbottom et al. 1995). We have clarified the definition of "volumetric excess ice content" following Harris et al. (1989) in the methodology section. We have also discussed the limitation of applying the ice content values in the CAPS data in our model development in the discussion section.

2. The authors suggest that high ice classes mapped on the Circum-Arctic Map of Permafrost and Ground ice Conditions (CAPS), designated in the submitted paper text as chf, chr, and dhf partly coincide with Yedoma areas and are "broadly oriented at the excess ice contents and distribution in intact Yedoma" (line 186-87).

The high ice landunit is considered representative of Yedoma. I'd like to point out the two maps below. Figure 1 shows the areas of chf, chr, dhf highlighted in red. Figure 2 C3 shows the distribution of Yedoma from Schuur et al (2015). The area mapped as chf, chr, and dhf is much more extensive than areas mapped as Yedoma. For example, a large portion of the Canadian Arctic Archipelago (CAA) is mapped as chr: continuous permafrost that has high visible ice content (>10%) and thin overburden cover (5-10m) and exposed bedrock. Most of the CAA was glaciated and includes no Yedoma. It therefore seems inappropriate to me that vast areas such as this include a considerable fraction of the high ice landunit in the modelling that represents Yedoma. The high ice landunit cryostratigraphy (70% excess ice in the upper ~8 m), may reasonably represent ice-rich Pleistocene deposits where permafrost has aggraded syngenetically, or local areas where large bodies of buried glacial ice occur just below the permafrost table. However, I can't think of situations where 70% excess ice content in the upper 8-10m would be reasonable for other deposits in which permafrost has formed epigenetically, given the typical decline in ice content with depth in epigenetic permafrost (e.g., French and Shur, 2010; Fig.2; Gilbert et al, 2019). I realize the authors acknowledge that the cryostratigraphies prescribed in the simulations are a coarse first-order approximation. However, the assumption that areas mapped with high ice content on the CAPS include significant areas where ground ice content is similar to thick Yedoma deposits, including those defined on the CAPS map as chr, seems particularly unrealistic and poorly justified.

It would have been simple to overlay CAPS and Yedoma areas in a GIS and examine the overlap within chf, chr, and dhf to better inform and substantiate landunit parameterizations/area weights.

Authors' reply: We agree that overlaying the Yedoma coverage information and the CAPS data can give a better interpretation over the Yedoma region. However, the excess ice content and located depth of ice wedges out of the Yedoma region is still unclear and lacks observational support. Although we fully acknowledge the importance of accurately representing different Yedoma cover in the model, for the sake of model representation of permafrost thaw processes, having an accurate projection over the Yedoma region does not improve the projections of the excess ice melt over the whole circum-arctic in general. Since the main purpose of our study is to represent permafrost thaw processes on a global scale, we make a decision to initialize different kinds of ice wedged ice as "Yedome type ice". As we understand this may not be fully representing reality, we added discussion on how these initialization scenarios brings uncertainties to surface subsidence projections in the discussion section. The high excess ice

content and the relatively cold climate where the high ice landunit is located make the wedged ice almost impossible to melt out completely by the end of the 21st century. The remaining part of the excess ice at the bottom has little effect on the surface subsidence. In this way, surface subsidence projections by 2100, initializing Yedoma type ice at the Yedoma region does not substantially affect the final result in our model simulations.

As we write in the discussion section, the purpose of simulation on top of this first-order scenario is to show how our model development can represent permafrost thaw processes on a global scale. Our modeling result shows that the current version of the CLM5 can represent permafrost degradation process with a wide range all the way from continuous to discontinuous permafrost and even no permafrost with the developed sub-grid representation of excess ice. The surface subsidence in the sub-grid representation produces greater heterogeneity to the land surface. Talik forming can also be retrieved during the degradation process. All of the above are novel progresses that no other state-of-the-art global land models can represent.

3. The authors provide a rationale for the excess ice content in the high ice landunit (for global simulations), which is commented on above, but provide little rationale for the medium and low ice content landunits (lines 193-200). One reference to an empirical study is provided (Line 197). The authors indicate that the excess ice content and distribution for the low ice landunit "account for a wide range of different excess ice conditions found throughout the permafrost domain" (line 197-198). It would have benefitted the reader if some of these excess ice conditions were elucidated, with pertinent references.

Authors' reply: The scenario we designed for the low ice landunit is based on previous studies that the segregated ice is widely distributed throughout the permafrost area. We have added more reference that segregated ice has been widely distributed throughout the permafrost area, both continuous and discontinuous permafrost (Line 239-246). We also provide an additional empirical excess ice volumetric content (25%) and located depth (ALT+0.2 ~ALT+1.2) to the low ice landunit. For the mid ice landunit, the volumetric content of excess ice and located depths are set in between the low and high ice landunits, which are also based on empirical data. As we mentioned, there is a lack of dataset on ground excess ice with enough information helpful for our sub-grid excess ice representation. For this reason, this is our best effort to make a possible scenario of excess ice distribution based on the best dataset (the CAPS data) at this time, even though it only provides generalized information and has been released for more than 20 years. Due to the lack of adequate information in excess ice distributions, the purpose of this study is not to make an accurate estimate of excess ice melt and surface subsidence in the 21st century, but rather to develop a functionable process within a land surface model on a global scale. Once there is a new generation of excess ice dataset, the CLM with sub-grid excess ice representation is able to be operational and give more accurate projections of excess ice melt and surface subsidences.

4. The authors state that subsidence of "more than 10 meters" (line 203) could occur if all ice melted from the high ice landunit in the global simulations. Earlier, the authors indicate that "we put excess ice in all the soil layers between 0.2 meters below the active layer and the bottom of hydrologically-active soil layer (8.5 meters)". As it is written, >10 m of subsidence is implied from thaw of <8.5m of ground.

Authors' reply: We have mentioned in the methodology section (Line 115) that the soil layer depth increases accordingly after adding excess ice. In this way, the soil thickness with excess ice added is thicker than 8.5 meters. For example, adding high ice landunit (70% volumetric excess ice content) in the soil layers with the original depths between 1 and 8.5 meters can

make the thickness of hydrologically-active soil 18.5 meters in total. > 10 m of subsidence is therefore possible in the simulation. We have added the content above in the main text to make the model design clearer.

5. The authors indicate that abundant field data in the Lena River delta provide a good basis for initializing ice conditions in refocused single-point simulations. I fully agree that simulations in areas with good available data is crucial. However, the authors in fact report no measurements of excess ice content anywhere in section 2.2 (only some volumetric ice contents are provided). It would benefit the reader to have some of these examples if there is abundant field data.

I am also confused by the authors' interpretation of the data that is presented in this section. For example, in Line 136 the authors indicate that ice wedges extend to 9 m depth in the Holocene terrain unit, and that there are volumetric ice contents of 60- 80%, citing Schwarmborn et al. (2002) and Langer et al. (2013). Schwarmborn et al. (2002) indicate much smaller ice wedges in the Holocene sediments: "and subaerial or buried ice wedges of 2–3m in height and width are common." (p. 123), and I cannot find wedge dimensions in Langer et al. (2013). I can only find mention of ice wedges that extend deeper (5-10 m) in the Ice Complex (Yedoma) unit in Schwarmborn et al. (2002).

The volumetric ice contents of 60-80% reported for the Holocene unit are seemingly from Langer et al. (2013, p.13) who indicate: "The elevated rims are usually covered with a dry moss layer underlain by wet sandy peat soils featuring massive ice wedges. The volumetric water/ice content of the peat soils typically ranges from 60 to 80%.". This value appears to refer to the volumetric ice content of the mineral soil C5 between ice wedges, rather than to an average representative value for a terrain unit or cross-section that includes both the icy soil matrix and ice wedges. At the scale of the modelling, this is what is pertinent, otherwise the contribution to ice content in the upper permafrost from ice wedges is not accounted for.

Authors' reply: For this single-point case for model evaluation, our goal is not to retrieve realistic excess ice melt, but rather to compare the model results from this study and from Westermann et al. (2016). Initializing realistic excess ice condition does not help the model evaluation in this case because the Lena River Delta has observed hardly any surface subsidence yet, making model-observation comparisons inapplicable. Alternatively, we make model-to-model intercomparisons to evaluate our developed physics and sub-grid representation. So we initialize excess ice strictly following that in Westermann et al. (2016). As a result, our sub-grid representation simulates comparable surface subsidences for each sub-grid landunit compared to Westermann et al. (2016), proving the reasonability of our developed sub-grid representation of excess ice. We have added the above clarification in the main text (Line 157-160).

6. Line 106: "The added ice is evenly distributed within each soil layer". In Figure 3, ice it not depicted as evenly distributed in the cross-sectional diagrams. Tile 4 shows large ice wedges, tile 3 a discontinuous (across the landunit) body of ice. The model does not represent ice in this way. These diagrams should reflect that ice is evenly distributed and consistent with the depictions showing "Present" and "Future" conditions.

Authors' reply: Although in the schematic figure and in reality, the ice is not distributed evenly, the framework of CLM and our developed sub-grid representation is able to convert this uneven distribution of excess ice into evenly-distributed excess ice landunits in the CLM. The relative

locations of excess ice bodies does not matter because CLM does not include horizontal heat and water fluxes (we have mentioned it in the discussion section). The set-up of excess ice in the CLM can be treated as "squeezing" all excess ice (of the same type) into a part of grid point with evenly-distributed excess ice and the other part of the grid point without excess ice.

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Comments on “Projecting circum-Arctic excess ground ice melt with a sub-grid representation in the Community Land Model” by Lei Cai et al submitted to The Cryosphere.

General

Permafrost soils usually contain large amount of ground ice. Its melting has significant impacts on infrastructure, landscape and hydrology. Ground ice also affects the timing and speed of permafrost thaw. This paper modelled the effects of ground ice on permafrost thaw using a sub-grid representation in the Community Land Model. They first test the implementation in Lena River delta. It shows that using three land units of different ground ice provides more realistic results than using one average ice land unit. The modelled thawing depths also very different among the three land units and from using the average ice content. Then they implemented the representation across the circum- arctic region using four land units (no ice, low, mid and high ice) and compared with the results using average ice content. The results shows more realistic pathways of permafrost degradation and a different total area with permafrost comparing to using average ice. The circum-arctic excess ice data are rough, the CAPS dataset is a very broad generalization of the complex ground ice conditions and how to use the dataset is not straightforward. However, this study does show some progress to include ground ice in a more realist way than previous studies (no excess ice, or using average for an entire grid) and it provides a general range of the large-scale impacts of such sub-grid differences. The paper is well prepared in language and figures.

Authors’ reply: Thank you very much for your valuable comments. We agree that the rough excess ice dataset is the main challenge when we conducted this study. Unfortunately, the CAPS data is still the best excess ice data available on the global scale although it was released more than 20 years ago. In this way, we have to design a tiling scheme to fit the CAPS data into the sub-grid framework we developed, which is not straightforward and contains fairly empirical estimates on excess ice contents and located depths. Although with the challenges on the initial condition of excess ice, we manage to convey through this manuscript that a sub-grid scale modeling of excess ice in the global land models is necessary for retrieving the permafrost dynamics in the circum-arctic regions, and we have had the modeling tool prepared before the new generation of excess ice dataset becomes available.

Major points

The test study shows very different active-layer thicknesses among the three land units and from the one-unit with average-ice (Figure 4). The paper did not provide much about the results of active-layer thickness for the circum-arctic modelling. It would be important to add this part in the results and analysis. Observations on ground subsidence is sparse and highly depend on the local conditions. An improved modelling of active-layer thickness would provide some support evidence about the usefulness of including excess ice in sub-grids.

Authors’ reply: The reason we did not mention the difference of active layer depth brought by the excess ice in the global case is that it is somewhat complicated because of a technical rather than scientific reason. Theoretically, the presence of excess ice makes the permafrost thermal regime more stable and a shallower active layer. However, it does not always show in the modeling case, because the model initializes soil into discrete layers that are with different thickness. For most land models, the thickness of each soil layer is not the same from top to bottom. Usually, deeper soil layers are also thicker. In the original soil set-up of the CLM5, the typical soil layer thickness for the depth between 0.5 to 1 meters is 0.15 meters, while that for the depth between 3 to 4 meters is more than 0.5 meters. In this way, for the regions with a

thicker active layer (e.g. > 2 meters), the presence of excess ice is not associated with a shallower active layer simply because the above soil layer is too thick (which also means the chunk of soil is bigger) to make the stable thermal regime distinguishable. We have now added some discussion in the main text to give readers some more insights.

"Compared to the grid average ice case, even more permafrost areas are sustained in the subgrid ice case" (Line 313-314). However, Figure 9 shows the permafrost area difference between sub-grid case and no ice case is similar to the difference between the average ice case and no ice case before the 2050, after that the latter reached about 1 million km2. That means the permafrost areas under average ice case and sub-grid ice case are similar before the 2050s. After that, the modelled permafrost area under average ice case is larger than under sub-grid ice case. In the last two panels in Figure 7, the shaded area in the second panel seems larger than the second panel. That is not consistent with the results in Figure 9. Not sure whether my understanding is correct. Any way, it would be useful and interesting to provide more explanation and analysis about the differences among these three cases (no ice, average ice and sub grid ice).

Authors' reply: In figure 9, we compared the actual area of permafrost in the sub-grid scale. For example, for a certain grid point with a total area of 0.2 million km2, only a landunit with 20% area weight has permafrost remaining (ALT <6.49 m). Then the area of permafrost for this grid point is 0.02 million km2. But in figure 7 and 8, we compare the permafrost degradation on the grid scale. In figure 7, the complete degradation of permafrost refers to the condition that all the sub-grid landunits in one grid cell are without permafrost. In figure 8, a grid cell is considered "discontinuous permafrost" if some landunit has permafrost while some others not. We have added more content in the figure caption to prevent misunderstandings.

The data about ground ice is rough and how to use the current data is based on some assumptions or artificial choices. It would important to indicate that uncertainties more clearly in the text (the paper already indicated that at different places).

Authors' reply: We have added more discussion on the uncertainty because of the excess ice initialization.

Minor points

Line 28-29: delete "enhance" or "improve".

Authors' reply: We have made the change as you recommended.

Lines 42-44, "The existence of excess ice and its distribution in permafrost can significantly affect the rate of permafrost thawing". It would be useful to add some references here.

Authors' reply: We have added more references.

Line 58: "over generations". It seems strange to say model versions as "generations". It would be clearer to say "in recent years" or so.

Authors' reply: We have made the change as you recommended.

Line 67: “Separate from this”, revised to “In addition”

Authors’ reply: We have made the change as you recommended.

Line 71-74. Check the grammar for this long sentence.

Authors’ reply: We have checked the grammar.

Line 74-95: “the depth distribution of ground ice can vary substantially on the order to 10-50 meters horizontally 75 and 10 meters vertically”. Is the depth to the top of ground ice or also including the thickness of ground ice? Probably you want to say both. Check and consider revising the sentence.

Authors’ reply: Actually here we just mean the depth of ground ice rather than both the depth and thickness since it is what the cited studies brought.

Line 165: “Satellite Phenology (SP) mode”, I do not know what is that. Some explanation would be helpful.

Authors’ reply: We have had an explanation for that. SP mode means it does not involve slowly evolving biogeochemical processes such as soil carbon accumulation (Line 180).

Line 220: “Have the same area fraction of low ice landunit”, You may add “(20%)” to make it clearer. What is the reason behind this assumption?

Authors’ reply: We make this assumption based on the fact that segregated excess ice is distributed widely throughout the permafrost region. So we assume that all the grid points in the CAPS data have some extent of low content ice. Since we define the volumetric content of excess ice in the low ice landunit as 25%, and the lowest category of excess ice in the CAPS data has 5% in volumetric excess ice content, we just assume that this 5% excess ice is contributed by 20% area weight of low content excess ice that is 25% in volumetric excess ice content.

You must have a percentage of land as no excess ice as the total percentage is less than 100% in Table 2 (e.g., for 5% CAPS, the no excess ice area would be 80%). If that is the case, it would be clearer to indicate the no excess ice areal percentage in Table 2, and the scheme actually uses four landunits (as shown in Figure 1) rather than three. For the grid-average ice case, you used the average of the three land units (Line 242) or the four land units?

Authors’ reply: We have made the change in Table 2 as you recommended.

Figure 3. The legend is in km2. You may provide the area of a grid or using % of the area of a grid.

Authors’ reply: Because the grid cell with a lower latitude has a larger area. We think using km2 can provide more information here.

Line 259-260: “A small amount of excess ice (24kg/m2) melts during the spinup period”, which case?

Authors’ reply: It is the average ice single-landunit case. We have added such information to the sentence to make it clear.

Lines 302-303: “We define the permafrost degradation in this study as when all the landunits in one grid cell has an active layer thickness greater than 6.5 meters”. That is different from the sentence in line 238. Probably the sentence in lines 302-303 is for how you treat the grid in figure 7. If so you can indicate its applications.

Authors’ reply: It is a matter of scales. In this study, only global simulation has permafrost degradation condition analyzed. For figure 7 and 8, we addressed analysis on the grid scale, and we regard full permafrost degradation when the permafrost in all landunit in one grid point has disappeared (ALT > 6.5m). For figure 9, we addressed analysis on the landunit scale to compare the actual permafrost area. In this way, we calculate the area of each landunit with permafrost degraded (ALT > 6.5 m). We have reworded these sentences to make this point clear.

Line 350: “as projected until 2100”, probably revise to “as we modelled”. No observations beyond present.

Authors’ reply: We have made the change as you recommended.

Line425, 438: “modelling”, “modelled”, be consistent with “Modeling” and “Modeled”

Authors’ reply: We have made the change as you recommended.

Projecting circum-Arctic excess ground ice melt with a sub-grid representation in the Community Land Model

Lei Cai[1], Hanna Lee[1], Kjetil Schanke Aas[2], Sebastian Westermann[2]

[1]NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, 5008, Bergen, Norway
[2]Department of Geosciences, University of Oslo, Oslo, 0315, Norway

Correspondence to: Lei Cai (leca@norceresearch.no)

Abstract To address the longstanding underrepresentation of the influences of highly variable ground ice content on the trajectory of permafrost conditions simulated in Earth System Models under a warming climate, we implement a sub-grid representation of excess ground ice within permafrost soils using the latest version of the Community Land Model (CLM5). Based on the original CLM5 tiling hierarchy, we duplicate the natural vegetated landunit by building extra tiles for up to three cryostratigraphies with different amounts of excess ice for each grid cell. For the same total amount of excess ice, introducing sub-grid variability in excess ice contents leads to different excess ice melting rates at the grid level. In addition, there are impacts on permafrost thermal properties and local hydrology with sub-grid representation. We evaluate this new development with single-point simulations at the Lena river delta, Siberia, where three sub-regions with distinctively different excess ice conditions are observed. A triple-landunit case accounting for this spatial variability conforms well to previous model studies for the Lena river delta and displays a markedly different dynamics of future excess ice thaw compared to a single-landunit case initialized with average excess ice contents. For global simulations, we prescribed a tiling scheme combined with our sub-grid representation to the global permafrost region using the dataset "Circum-Arctic Map of Permafrost and Ground-Ice Conditions" (Brown et al., 1997). The sub-grid scale excess ice produces significant melting of excess ice under a warming climate and enhances the representation of sub-grid variability of surface subsidence on a global scale. Our model development makes it possible to portray more details on the permafrost degradation trajectory depending on the sub-grid soil thermal regime and excess ice melting, which also shows a strong indication that accounting for excess ice is a prerequisite of a reasonable projection of permafrost thaw. The modeled permafrost degradation with sub-grid excess ice follows the pathway that continuous permafrost transforms into discontinuous permafrost before it disappears, including surface subsidence and talik formation, which are highly permafrost-relevant landscape changes excluded from most land models. Our development of sub-grid representation of excess ice demonstrates a way forward to ~~enhance~~ improve the realism of excess ice melt in global land models, but further developments rely on additional global observational datasets on both the horizontal and vertical distributions of excess ground ice.

1. Introduction

Permafrost soils are often characterized by different types of ground ice that can exceed the pore space (Brown et al. 1997; Zhang et al., 1999). The presence of such "excess" ground ice can alter the permafrost thermal regime and landscape structure. Widespread thawing of permafrost is expected in a warmer future climate and modeling studies suggest large-scale degradation of near-surface permafrost at the end of the 21st century (Lawrence et al., 2008 & 2011). Melting of ground ice due to active layer thickening releases water in the form

of surface and/or subsurface runoff, causing surface subsidence and modifying the local hydrological cycle (West and Plug, 2008; Grosse et al., 2011; Kokelj et al., 2013; Westermann et al., 2016). In addition to containing ground ice, some permafrost soils store massive amounts of carbon, which could be released to the atmosphere in the form of greenhouse gases upon thawing (Walter et al., 2006; Zimov et al., 2006; Schuur et al., 2008), possibly making a positive feedback to amplify future climate change (Koven et al., 2011; Schaefer et al., 2014; Burke et al., 2013). The existence of excess ice and its distribution in permafrost can significantly affect the rate of permafrost thawing (Westermann et al., 2016; Nitzbon et al., 2020), and in turn, the rate of soil carbon release (Hugelius et al., 2014; Schuur et al., 2015; Turetsky et al., 2019). Therefore, better projections of excess ice melt are critical to improve our understanding of the impacts of permafrost thaw on corresponding climatic impacts.

Previous studies address excess ice modeling on the local or regional scale, in which the small study area makes it possible for detailed configurations of the cryostratigraphy of permafrost and excess ice based on observations. Simulations for the Lena river delta have retrieved the permafrost thermal dynamics fairly close to the observations with excess ice incorporated in the modeling (Westermann et al., 2016). A two-tile approach allowing lateral heat exchange between two land elements demonstrated that maintaining thermokarst ponds requires the heat loss from water to the surrounding land (Langer et al., 2016). A similar tiling approach has been applied to projecting the landscape changes due to permafrost thaw for ice-wedge polygons and peat plateaus with different features of ice melting and surface subsidence (Aas et al., 2019; Nitzbon et al., 2019).

On the global scale, the land components of Earth System Models (ESMs) have significant capabilities of representing key permafrost physics. In the Community Land Model (CLM), for example, the representation of permafrost-associated processes has been continuously improving~~ed over generations~~. By including key thermal and hydrological processes of permafrost, the CLM version 4 (CLM4) has reasonably reproduced the global distribution of permafrost (Lawrence et al., 2008; Lawrence et al., 2012; Slater and Lawrence, 2013). Projections based on the CLM4 under its highest warming scenario (RCP8.5) have shown over 50% degradation of near-surface permafrost by 2100 (Lawrence et al., 2012). Moreover, the recently released CLM5 has more advanced representations of many biogeophysical and biogeochemical processes (Lawrence et al., 2019). A refined soil profile and upgraded snow accumulation and densification scheme in the CLM5 could contribute to simulating more realistic permafrost thermal regimes, whereas upgrades on biogeochemistry improve simulations of soil carbon release in response to permafrost thaw. In addition~~Separate from this~~, an excess ice physics scheme has been implemented in CLM4.5 (CLM4.5_EXICE) by Lee et al. (2014), which allowed for the first-order simulation of surface subsidence globally by modeling excess ice melt under a warming climate.

The homogeneous distribution of excess ice throughout the grid cell in CLM4.5_EXICE (Lee et al., 2014) could cause biases in thaw trajectories in the warming climate. In nature, excess ice forms in a highly localized manner due to a variety of accumulation processes. For instance, segregated ice formed during frost heave differs substantially in excess ice morphology from ice wedges that are formed from repeated frost cracking and freezing of penetrating water. Field measurements illustrate that the depth distribution of ground ice can vary substantially on the order to 10-50 meters horizontally and 0-10 meters vertically (Pascale et al., 2008; Fritz et al., 2011). The horizontal grid spacing of ESMs, on the other hand, usually ranges from one to two degrees (~100-200km horizontal scale), which makes it impossible to represent localized excess ice. The mismatch in spatial scale

between model and the real world raises concerns for the reliability of excess ice modeling in ESMs. Aside from the homogenously-initialized excess ice in the grid cell, CLM4.5_EXICE initializes excess ice in the same soil depths globally (below 1m), regardless of the varying active layer thickness in circum-Arctic permafrost areas (Lee et al., 2014). Such deficiencies in excess ice parameterization hamper global projections of permafrost thaw including excess ice with ESMs.

To narrow the gap between the high spatial variability of excess ice and the coarse grid spacing in the ESMs, we applied a sub-grid approach in representing excess ice in permafrost soils within the CLM5 to investigate how presence and melting of excess ice affect land surface physics under a warming climate. We conducted idealized single-point simulations to examine the robustness of model development. We furthermore conducted global simulations using a first-order estimate for the spatial distribution of excess ice and associated cryostratigraphies, aiming to present a model framework that can eventually bring the modeling ~~We furthermore conducted global simulations using a prescribed set of sub-grid scale excess ice conditions, aiming to bring the modeling of excess ice melt and the corresponding impacts on the global scale~~ towards a higher accuracy. Due to the lack of information in global excess ice conditions, it is not the aim of this study to accurately project excess ice melt and surface subsidence in the 21st century, but rather to develop a functionable process within a land surface model on a global scale. The CLM5 with sub-grid excess ice representation developed through this study would be ready to serve as a proper simulation tool on further advancing global excess ice modeling once new datasets become available.

2. Methodology

2.1 Sub-grid representation of excess ice in the CLM5

The CLM5 model utilizes a three-level tiling hierarchy to represent sub-grid heterogeneity of landscapes, which are (from top to bottom) landunits, columns, and patches (Lawrence et al., 2019). There is only one column (the natural soil column) that is under the natural vegetated landunit, which represents soil including permafrost. In this study, we modify the CLM5 tiling hierarchy by duplicating the natural vegetated landunit, making extra landunits for prescribing up to three different excess ice conditions in permafrost (Figure 1). The original natural vegetated landunit is considered as "natural vegetated with no excess ice" (hereafter no ice landunit), while we denote the additional landunits as "natural vegetated with low content of excess ice" (hereafter the low ice landunit), "natural vegetated with medium content of excess ice" (hereafter the mid ice landunit), and "natural vegetated with high content of excess ice" (hereafter the high ice landunit). The sub-grid initial conditions of excess ice are imported as part of the surface data, which includes the variables of volumetric excess ice contents, depths of the top and bottom soil layer of added excess ice, and the area weights of the four landunits.

We adopted the excess ice physics from CLM4.5_EXICE (Lee et al., 2014), including thermodynamic and hydrological processes. The added excess ice is evenly distributed within each soil layer. Note that the original CLM5 model already represents the dynamics of pore ice. Our representation of excess ice physics only addresses the ground ice bodies that exceed soil pore space. The volumetric excess ice content in this study is defined as the ratio of the volume of excess ice in a soil layer to the volume of the whole soil layer. For example, a 50%

volumetric content of excess ice means the excess ice body occupies 50% volume of a soil layer, while the rest of soil (and pore ice) occupies the other 50% volume of the soil layer. If not otherwise notified, the parameter of volumetric ice content in this manuscript refers only to that of excess ice bodies. After adding excess ice, the soil layer thickness increases accordingly. Because ice density is considered constant, the increase of soil layer thickness is linearly proportional to the volumetric content of excess ice. For example, adding an excess ice body with a 50% volumetric excess ice content doubles the soil layer thickness of the corresponding soil layer. The revised algorithm for thermal conductivity and heat capacity of soil involves the effects of added excess ice, while the revised phase change energy equation allows excess ice to melt. The meltwater adds to soil liquid water in the same soil layer, and it can move to the above layer if the original layer is saturated. Such numerical implementation replicates how the melt excess ice eventually converts to runoff and discharges from the soil in case of well-drained conditions. As excess ice melts, soil layer thickness decreases, which corresponds to surface subsidence due to excess ice melt. In our model parameterization, excess ice only melts and does not re-form since the applied excess ice physics does not account for the different ice formation processes.

Aside from sub-grid tiles for excess ice, we acknowledge that the version upgrade from CLM4.5 to CLM5 as the base model modifies the results of excess ice melt compared to the results from Lee et al. (2014). By default, CLM5 represents soil with a 25-layer profile, for which the top 20 hydrologically-active layers cover 8.5 meters of soil. There are additional 10 soil layers and it is 4.7 meters deeper compared to the default hydrologically-active soil layer profile in CLM4.5, not to mention the substantially more complex biogeophysical processes (Lawrence et al., 2019). Therefore, we developed the sub-grid representation of excess ice within the framework of the latest version of CLM. The duplicated landunits prolong computation time by roughly 10% compared to the original CLM5. We are, therefore, confident that our model development is highly efficient in addressing the sub-grid excess ice and subsequent permafrost thaw.

2.2 Single-point simulations for the Lena river delta, Siberia

We conduct single-point simulations for the Lena River delta and compare the CLM5 model results to reference simulations with the CryoGrid3 model for the same location (Westermann et al., 2016). Abundant background information is available on the soil and ground ice dynamics from both observation and modeling, making the Lena river delta a suitable location to further evaluate our model development. The Lena river delta can be broadly categorized into three different geomorphological units that have distinctively different subsurface cryostratigraphies of excess ice (Schneider et al., 2009; Ulrich et al., 2009). In the eastern and central part of the river delta, ground ice has been accumulated in the comparatively warm Holocene climate. The subsurface sediments (hereafter denoted as "Holocene ground ice terrain") are generally super-saturated with wedge ice that can extend up to 9 meters underground with the volumetric ~~ice~~ contents of total ground ice (pore ice + excess ice) ranging from 60-80% (Schwamborn et al., 2002; Langer et al., 2013). On the other hand, higher excess ice contents are found in Pleistocene sediments in the Lena River Delta (hereafter the "Yedoma Ice complex"), which are characterized by Yedoma type ground ice (Schirrmeister et al., 2013), which can reach depths of up to 20-25 meters deep and volumetric contents of total ground ice~~volumetric ice contents as high as 90%~~ (Schwamborn et al., 2002; Schirrmeister et al., 2003 and 2011). Finally, the Northwestern part of the delta features sandy sediments and is characterized by low excess ice contents (hereafter denoted the "no excess ice terrain"; Rachold and

706 Grigoriev, 1999; Schwamborn et al., 2002).

707 We determine the area weights of excess ice landunits in one single point based on the spatial pattern of three
708 subregions (Fedorova et al., 2015). The cryostratigraphy and the volumetric contents of excess ice~~excess ice~~
709 ~~contents~~ strictly follow those in Westermann et al. (2016). Note that the excess ice initialization scenario in
710 Westermann et al. (2016) does not necessarily represent the realistic excess ice condition for the Lena river delta.
711 The purpose of applying the same excess ice cryostratigraphy as in Westermman et al. (2016) is to evaluate our
712 model development by addressing intercomparisons between model results. Meanwhile, we did not customize soil
713 properties for different landunits as in Westermann et al. (2016), as our model development does not support
714 varying soil properties for different sub-grid landunits. We also directly apply the snow accumulation physics in
715 the CLM rather than customizing the snow density. By default, the current model does not form thermokarst lakes
716 as the meltwater from excess ice melt becomes surface runoff and is removed from the grid cell. To apply the sub-
717 grid representation, we initialize the case with three landunits (the triple-landunit case) that respectively represent
718 the three terraces in the Lena river delta. We also initialize an "average ice single-landunit" case without the sub-
719 grid representation of excess ice. The excess ice amount for each soil layer in the average ice single-landunit case
720 is initially the same as that in the triple-landunit case. The volumetric ~~ice~~ content of excess ice is determined by
721 spatial averaging those for three excess ice landunits in the triple-landunit case. Detailed information on the
722 applied excess ice conditions for both cases is listed in Table 1.

723 We employed the single-point forcing data from in Westermann et al. (2016) for the Lena river delta from
724 1901 to 2100, which is based on the CRU-NCEP (http://dods.extra.cea.fr/data/p529viov/cruncep/) data set for the
725 historical period (1901-2005) and the CCSM4 model output under the RCP4.5 scenario for the projected period
726 (2006-2100), but downscaled with in-situ observations. We run 100-year spin-up simulations in order to stabilize
727 the permafrost thermal regime after adding excess ice. Spin-up simulations are produced by running the model
728 with cycled 1901-1920 climatological data. The purpose of spin-up simulations is to stabilize ground temperatures
729 and volumes of excess ice bodies. The 100-year length for spin-up is sufficient, as the model is run in Satellite
730 Phenology (SP) mode that does not involve slowly evolving biogeochemical processes such as soil carbon
731 accumulation. Moreover, we address idealized single-point simulations for additional permafrost locations with
732 both continental and maritime climate that showcase the difference to Lee et al. (2014), the results of which are
733 included in the Supplementary material.

734 **2.3 Global simulations of excess ice melt**

735 The information available for the spatial distribution of excess ice and associated cryostratigraphies on the
736 global scale is generally not as detailed as in the Lena river delta due to the lack of observations. For our global
737 simulations we employ the widely used "Circum-Arctic Map of Permafrost and Ground-Ice Conditions" (hereafter
738 the CAPS data; Brown et al., 2002) as data source, while we translate the ground ice condition in the CAPS data
739 to different excess ice stratigraphies as model input data. The CAPS permafrost map categorizes the global
740 permafrost area into classes coded by three factors (i) permafrost extent (c = continuous, d = discontinuous, s =
741 sporadic, and i = isolated), (ii) visible ground ice content (h = high, m = medium, and l = low), and (iii) terrain
742 and overburden (f = lowlands, highlands, and intra- and intermontane depressions characterized by thick
743 overburden cover, and r = mountains, highlands ridges, and plateaus characterized by thin overburden cover and
744 exposed bedrock), resulting in more than 20 different varieties in permafrost characteristics (Figure 2). For the

simulations, we only use the CAPS distinction between the three classes: high, medium and low ice contents. We qualitatively categorize excess ice types with typical cryostratigraphies for which observations are available, recognizing that this is a crude first-guess of the global distribution of ground ice which needs to be be improved in future studies.

The high ice CAPS classes (e.g. chf, chr, and dhf) in central and eastern Siberia, as well as in Alaska, partly coincide with Yedoma regions (Kanevskiy et al., 2011; Grosse et al., 2013). The cryostratigraphy of the high ice landunit is therefore broadly oriented at the excess ice contents and distribution in intact Yedoma, which is characterized by massive ice wedges leading to typical average volumetric content of total ground ice in the range from 60% to 90% (Schwamborn et al., 2002; Kanevskiy et al., 2011). We therefore set the volumetric ~~excess ice~~ content of excess ice in the high ice landunit to 70%, and we put excess ice in all the soil layers between 0.2 meters below the active layer and the bottom of hydrologically-active soil layer (8.5 meters). The onset depth of the excess ice just below the active layer is based on the assumption of active ice aggradation which occurs at or below the permafrost table, e.g. the formation of wedge or segregation ice. Initializing high content excess ice throughout the whole soil layer imitates the cryostratigraphy of Yedoma type ice, while a certain amount of high ice landunit locates out of the observed Yedoma regions (Schuur et al., 2015). The effects, limitations, and potential improvements of this initialization scenario will be mentioned in the discussion section. For the low ice landunit, we assume both a significantly lower volumetric excess ice content and a smaller vertical extent of the excess ice body. The volumetric excess ice content is set to 25%, and we add excess ice at soil layers within 0.2 to 1.2 meters below the active layer, which in particular represents sediments with segregated ice (e.g. Cable et al., 2018), but also accounts for a wide range of different excess ice conditions found throughout the permafrost domain. For the mid ice landunit, we set the volumetric excess ice content to 45% and put excess ice within 0.2 to 2.2 meters below the active layer, making the volumetric excess ice content and vertical extent of which in between those for the low and high ice landunits. The cryostratigraphies determine that excess ice melt in the low ice landunit can result in a maximum of 0.36 meters of surface subsidence, while excess ice melt in the medium ice landunit can result in a maximum of 1.78 m of surface subsidence. For the high ice landunit, the surface subsidence can be more than 10 meters if all excess ice melts, which is expected to vary in space because of the different active layer thickness. For all three landunits, the active layer thickness is determined by the soil temperature profile by the end of the spinup in a no ice case, which is the simulation by the original CLM5 model without excess ice incorporated. Non-permafrost regions in the CAPS data are assigned the no ice landunit for 100% of their area. We emphasize that the prescribed cryostratigraphies are a coarse first-order approximation that can by no means represent the wide variety of true ground ice conditions found in the permafrost domain. Nevertheless, this makes it possible to gauge the effect of excess ice melt on future projections of the permafrost thermal regime, when compared to "traditional" reference simulations without excess ice.

We design a tiling scheme prescribing the assignment of landunits for each CAPS class based on previous observations and empirical estimates (Table 2). All CAPS classes in this study are categorized into three levels of volumetric ice content (5%, 15%, and 25%) that are converted from the ranges (<10%, 10-20%, and >20%) in the original CAPS data. The goal of our tiling scheme is to determine a combination of area weights of three excess ice landunits for each CAPS class, making the spatially averaged volumetric ~~ice~~ content of excess ice the same as that for the CAPS class. We assume that all CAPS classes have the same area fraction (20%) of the low ice landunit,

and the CAPS classes with a higher ice content are due to the existence of the landunits with a higher content excess ice. We make this assumption based on previous studies that the segregated ice is widely distributed in permafrost. Observational studies have found segregated ice bodies in various continuous permafrost regions across the circum-arctic including West Central Alaska (Kanevskiy et al., 2014), Nunavik, Canada (Calmels and Allard, 2008), and Svalbard (Cable et al., 2018). In discontinuous permafrost regions, segregated ice bodies also commonly exist underneath Palsas and Lithasas, including Fennoscandia (Seppälä, 2011), Altai and Sayan, Russia (Iwanhana et al., 2012), Himalayas (Wünnemann et al., 2008), and Mongolia (Sharkhuu et al., 1999). The volumetric content of visible segregated ice bodies mentioned above ranges widely from 10-50% (Gilbert et al., 2016).

Given the tiling scheme~~ice content~~ prescribed above, all CAPS classes are assigned a 20% area of low ice landunit. Correspondingly, the CAPS classes with 15% volumetric ice content are assigned another 14% area weight for mid ice landunit on top of the CAPS classes with 5% volumetric ice content, while the CAPS classes with 25% volumetric ice are assigned another 22% area for high ice landunit on top of the CAPS classes with 15% volumetric ice content. The classes of "chf" and "chr" are the exceptions as their corresponding regions are typically with the landscape of Yedoma and/or ice wedge polygonal tundra (Kanevskiy et al., 2011; Gross et al., 2013). We therefore assign only the low and high ice landunits for these two CAPS classes. Summing up the landunit fractions for all the CAPS grid cells within each CLM grid cell obtains the area weights on the grid level that are stored in the surface data file. Figure 3 shows a schematic plot for the initialization scenario and the area covered by different excess ice landunits as the result of sub-grid excess ice initialization in the global simulation case. Note that excess ice for some regions (e.g. Southern Norway and the Alps) can completely melt out during the spinup period since the CLM initial condition prescribes overly warm (non-permafrost) soil temperature for these regions.

In this study, we define the grid cells/landunits with permafrost as the ones having at least one hydrologically active soil layer that has been frozen in the last consecutive 24 months. In this case, we define permafrost degradation when all landunits in one grid point are~~degraded permafrost as permafrost landunits~~ with active layer thickness more than 6.5 meters. We also prepare a "grid-average ice case" by applying the same total amount of excess ice as in the sub-grid ice case in each soil layer, but using only one landunit instead of three that account for the sub-grid variability of excess ice. The volumetric ~~excess ice~~ content of excess ice in the single landunit is calculated as the spatial average of those in the three landunits in the triple-landunit case. This grid-average ice case provides a reference to evaluate the effects of the sub-grid excess ice representation on the global scale. Finally, we simulate a reference case without excess ice, denoted the "no ice case" in the following. Details on the three cases for the global simulations are listed in Table 3. All global cases are forced by the 3rd version of Global Soil Wetness Project forcing data (GSWP3; Kim et al., 2012), running in the Satellite Phenology (SP) mode. The International Land Atmosphere Model Benchmarking (ILAMB; Collier et al., 2018) project has indicated the superior performance of GSWP3 data forcing the CLM5 in the SP-only mode (http://webext.cgd.ucar.edu/I20TR/_build_090817_CLM50SPONLY_CRUNCEP_GSWP3_WFDEI/index.html). We conducted a 100-year spin-up using the 1901-1920 climatology before conducting historical period simulations covering 1901-2005. The anomaly forcing under the RCP8.5 scenario on top of the 1982-2005 climatology forces simulations in the projected period.

3. Result

3.1 Excess ice melt simulations for Lena River delta cryostratigraphies

By the end of the spinup in the triple-landunit case, the active layer thickness is 0.85 m, 0.55 m, and 0.45 m for the ice-poor terrain, the Holocene ice wedge terrain, and the Yedoma ice complex, respectively. On the other hand, the active layer thickness for the average ice single-landunit case is 0.85 m, which is the same as in the no excess ice terrain in the triple-landunit case. For the average ice single-landunit case, a~~A~~ small amount of excess ice (24kg/m^2) melts during the spinup period, resulting in 2.6 cm surface subsidence throughout the grid.

For the Yedoma ice complex, very little excess ice melt in the 1950s, and it stabilizes afterwards until the late 2000s when substantial ice melt and surface subsidence starts to happen. For the Holocene ground ice terrain, there is no excess ice melt before the late 2010s. By the year 2100, the Yedoma ice complex has exhibited nearly 4 meters of surface subsidence, while the Holocene ground ice terrain has about 0.6 meters of surface subsidence (Figure 4). For the average ice single-landunit case, the noticeable excess ice melt and surface subsidence starts in the late 2010s, which creates about 0.5 meters of surface subsidence by 2100. The magnitude of surface subsidence in the average ice single-landunit case is lower than both the Holocene ground ice terrain and the Yedoma ice complex in the triple-landunit case.

On the grid scale, the total excess ice melt is higher in the average ice single-landunit case than in the triple-landunit case (Figure 5). By the year 2100, the average ice single-landunit case has about 30 kg/m^2 more excess ice melt than the triple-landunit case. The difference in excess ice on the grid level results from the different volumetric ~~ice~~ content of excess ice caused by the spatial averaging. In this way, the sub-grid representation of excess ice can potentially also provide more detailed and realistic representation of model variables on the grid level. This is particularly important for the CLM5, which serves as the land component in Earth System Models, which requires the coupling between interacting components on the grid level.

Compared to Westermann et al. (2016), the CLM5 with sub-grid excess ice simulates slightly less (~ 20% less) surface subsidence by 2100 for both the central delta and ice complex. We consider this a good agreement as we do not expect a closer fit of the model results due to substantial differences in the model physics (for example, the Cryogrid3 simulations in Westermann et al. (2106) lack a representation of the subsurface water cycle). What is in common between these two studies is the earlier start of excess ice melt and more surface subsidence in the ice complex than in the central delta. The CLM5 with sub-grid excess ice also exhibits the varying active layer thickness with different excess ice conditions as Cryogrid3 does. These results suggest that the new model development enables small-scale variability in excess ice melt and subsequent impacts in agreement with previously published modeling efforts.

3.2 Global projection of permafrost thaw and excess ice melt

Single-point simulations have shown that the varying excess ice cryostratigraphies for different landunits result in sub-grid variabilities of excess ice melt and surface subsidence under the warming climate. The same features remain in the sub-grid ice case within the global simulations that excess ice in the low ice landunit can completely melt out throughout the circum-Arctic permafrost region by the end of the 21st century (Figure 6). The modeled magnitude of surface subsidence is similar to the ~10 cm surface subsidence observed in Barrow and West Dock in the early 21st century (Shiklomanov et al., 2013; Streleskiy et al., 2017). The magnitude of surface

subsidence is also comparable to the 1-4 cm decade^{-1} surface subsidence rate on average over the North Slope of Alaska observed by satellite measurements since the 1990s (Liu et al., 2010). In comparison, the absence of surface subsidence for Arctic Alaska modeled by Lee et al. (2014) is due to an overly deep (1 m deep) excess ice initialization depth. By the year 2100, most ice in the medium ice landunit melts away in the sub-arctic region, while there is less ice melt in the colder regions such as the North Slope of Alaska and the central Siberia. The high ice landunit has the greatest surface subsidence among the three because of its high excess ice content, leading to 2-5 meters of surface subsidence by the year 2100.

The existence of excess ice modulates the thermal regime of permafrost soil and is a major control on permafrost degradation trajectories in a warming climate. ~~We define the permafrost degradation in this study as when all the landunits in one grid cell has an active layer thickness greater than 6.5 meters.~~ Permafrost with excess ice consistently exhibits delayed permafrost degradation compared to the no ice case (Figure 7). For the no ice case modeled by the original CLM5, more than half of the permafrost area undergoes degradation by the end of the 21st century. By 2100, the only areas where permafrost remains are the North Slope of Alaska, Northern Canada, and the majority of the land area in Northern Siberia. The areas with remaining permafrost in the year 2100 under the RCP8.5 scenarios are substantially larger compared to the CLM4 simulations, in which nearly all permafrost in Eurasia becomes degraded (Lawrence et al., 2012). For the grid-average ice case, the presence of excess ice stabilizes the permafrost thermal regime and thus sustains a larger permafrost area on a global scale in the simulation. For example, permafrost areas in some subarctic regions in the eastern and western Siberia, as well as part of the Arctic coastal regions in Yukon Territory, Canada, remain in the grid-average ice case by 2100. Compared to the grid-average ice case, even more permafrost areas are sustained in the sub-grid ice case, most of which are located in southern Siberia. In the subarctic regions in Alaska and Northwest Canada as well as part of the central Siberia, permafrost degradation is delayed from the 2040s in the grid ice case to the 2080s in the sub-grid ice case. We emphasize that permafrost is only sustained according to the accepted temperature-based definition (ground material at temperature below zero for two consecutive years), but excess ice continuously melts in this process, which energetically is a different mode of permafrost degradation, similar to a negative mass balance of glaciers and ice sheets.

In the sub-grid ice case, the landunits with high excess ice contents lead to more grid points for which permafrost conditions remain in the year 2100 compared to the grid-average ice case. On the other hand, permafrost with excess ice only covers a fraction of a grid point. Among the permafrost degradation trajectories in the three global simulation cases (Figure 8), the sub-grid ice case can provide a more detailed picture on the timing of permafrost degradation. Grid cells become 'partially degraded permafrost' if landunits with excess ice still contain permafrost, which phenomenologically is a more realistic representation that also makes it possible to represent the permafrost distribution in the discontinuous and sporadic permafrost zones. On the other hand, only "fully degraded permafrost" and "remaining permafrost" can be distinguished for the no ice and grid-average ice case. Under the warming climate in the 21st century, the existence of excess ice, especially the high content of excess ice, has a stabilizing effect on soil temperature that delay the disappearance of permafrost on the sub-grid level. Therefore, by the year 2100, there are regions with partially degraded permafrost in between intact and degraded permafrost (Figure 8). For example in western Siberia, the Pacific coastal area of eastern Siberia, Northwestern Canada, and along the Brooks Range in Alaska, taliks form for landunits with low excess ice contents which leads to partially degraded permafrost regions. Therefore, permafrost degradation exhibits a

gradual transition from continuous to discontinuous permafrost, and to non-permafrost regions. Some of these regions also encounter substantial surface subsidence in the high ice landunit (> 5 m) (Figure 6).

We further compare the total permafrost area (defined as landunits with active layer thickness < 6.5 meters) in the three cases throughout time. The differences in permafrost area increase from the grid-average ice case and sub-grid ice case to the no ice case at a rate of 1000 km^2 per year until 2050 (Figure 9). After 2050, the area difference of permafrost in the grid-average ice case and no ice cases rapidly increases, which reaches nearly one million km^2 by 2100. In the sub-grid ice case, the rate of increase remains relatively unchanged after 2050, resulting in an about 0.2 million km^2 larger permafrost area than that in the no ice case.

4. Discussion

The aim of the sub-grid excess ice representation in the CLM5 is to facilitate long-term global projection of excess ice melt and surface subsidence in the permafrost regions, but the corresponding observational data for model evaluation is sparse, considering especially that drastic excess ice melt as modeled~~projected~~ until 2100 is only observed in few locations today (e.g. Günther et al., 2015). In the following, we discuss the challenges and limitations of the sub-grid excess ice framework, and how this sub-grid representation can potentially help the development of other CLM components.

Both single-point and global test simulations in this study have shown that excess ice melts under a warming climate is sensitive to its initialization depth. The active-layer-dependent excess ice initialization in this study in the global simulation (sub-grid excess ice case) yields excess ice melt and surface subsidence rates in the early 2000s that are comparable to observations. The lower depths of the assumed excess ice body controls the termination of excess ice melt which at the same time determines the onset of talik formation in many permafrost areas. Due to the scarcity of observational data, it is unclear to what extent the cryostratigraphies assumed in our tiling scheme can reproduce the true vertical extent of excess ice bodies at least in a statistical sense. Even so, we manage to make the prescribed excess ice condition as close to the previous results as possible. Firstly, our tiling scheme on the large scale strictly follows the CAPS data (Brown et al., 2002) in terms of the volumetric excess ice content. Furthermore, statistics by Zhang et al. (2000) suggest the ranges of the vertical extent of ice-rich permafrost of 0-2 meters and 2-4 meters respectively for the CAPS classes with low (5%) and medium (15%) ice content. Comparatively, the vertical extents permafrost with excess ice prescribed by our tiling scheme are respectively 1.36 meters and 3.78 meters for the same CAPS classes, both of which lie within the ranges in Zhang et al. (2000). The vertical extent of ice-rich permafrost for the high ice landunit is much higher than that (4-6 meters) in Zhang et al. (2000), but the unmelted part of the ice bodies does not strongly affect the overall rate of excess ice melt, although the remaining ice can slightly change soil temperature and moisture of the surrounding permafrost. We therefore imply that our high ice landunit initialization would not induce a strong bias in excess ice melt projection in the 21st century.

Due to the lack of excess ice datasets and observational evidence, the excess ice initialization scenarios in the global simulation cases involve empirical estimates and simplifications, which could bring biases to the projection of excess ice melt and surface subsidence. We apply the volumetric content of ground ice in the CAPS data approximately as the volumetric content of excess ice during initialization as the CAPS data is mostly based

on visible ice bodies (Heginbottom et al., 1995), not to mention the determination of volumetric contents of excess ice for three landunits also result from sparse observations and empirical estimates. The prescribed excess ice cryostratigraphies ignore~~s~~ ice morphology and ~~possible~~ the variation~~s~~ of volumetric content of excess ice~~ice content~~ with soil depth, regarding ~~initializing~~ excess ice as homogeneous " ice cubes"~~ with a homogeneous ice content~~. For the high ice landunit, we simplify the cryostratigraphy initialization to Yedoma type ice, which prescribes overly thick excess ice bodies out of the Yedoma regions (Schurr et al., 2015). A deficiency in the current version of source code disables us to initialize non-Yedoma wedged ice for the high ice landunit out of the Yedoma region. Future versions of our model development will have more freedom in excess ice stratigraphy configuration, which makes it possible to prescribe different cryostratigraphies of the same landunit (e.g. the high ice landunit) for different locations. Furthermore, excess ice stratigraphy ~~We simplify the excess iceice content initialization for two reasons. Firstly, the model development serves the land component of an earth system model that focuses on large-scale changes. Furthermore, there is not enough observational evidence for us to prescribe the variability of excess ice content with geographic locations and soil depths~~. ~~Because of~~~~Due to~~ Because of the above~~ such~~ shortcomings in the excess ice initialization, we do not expect the modeled excess ice melt in this study to be an adequate representation of reality yet, while~~but~~ improved observational data sets of excess ice contents and cyostratigraphies could be directly ingested to yield improved results. ~~Our model development is capable of supporting three different excess ice landunits for each grid point, but the cryostratigraphies assumed in the initialization in principle also vary in space.~~ However, ~~at present,~~ a spatially distributed global dataset with quantitative information on excess ice stratigraphies does not exist at present. We emphasize that for a better projection of excess ice melt, more observational data of excess ice distribution and surface subsidence is required to further evaluate and validate the new model implementation of excess ice. On the regional scale, Jorgenson et al. (2008) presented a permafrost map of total ground ice volume for the uppermost 5 meters of permafrost based on both observations and estimates for Alaska. In addition, O'Neill et al. (2019) compiled permafrost maps for Northern Canada by paleographic modeling, mapping the abundances of three types of excess ice respectively. Further improvements of model results depend~~are dependent~~ on additional observationally constrained datasets of excess ice conditions on the global scale.

The area weights of the excess ice landunits (Table 2) in the global simulation are obtained from the higher-resolution CAPS points located within a CLM grid cell. However, complex landscape development, such as thermokarst ponds, requires knowledge of the meter-scale distribution, for example the extent and geometry of individual ice wedges (Langer et al., 2016; Nitzbon et al., 2019), which cannot be represented with the still coarse-scale excess ice classes from the CAPS map. One possible solution to represent this could be to include another layer of sub-grid tiles below the CLM landunit level, where the individual tiles can interact laterally. This would allow for the representation of small-scale permafrost features within a large-scale landunit with a given excess ice content. An example of how this could work is given by Aas et al. (2019) who simulated both polygonal tundra and peat plateaus with a two-tile interactive setup. This is also similar to the recent representation of hillslope hydrology by Swenson et al. (2019), where sub-grid tiles (on the column level in CLM) were used to represent different elements in a representative hillslope. In the future development of CLM, this could be part of a more generic tiling system where lateral heat and mass fluxes could be switched on and off to represent a wide range of land surface processes that are currently ignored or parameterized in LSMs. Fisher and Koven (2020) have discussed the challenges and opportunities in such an adaptive and generic tiling system. We would also advocate

for enhancing current tiling schemes in such a direction, which could substantially improve the realism in the representation of permafrost landscapes in LSMs. However, the success of such a tiling approach will rely heavily on the availability of adequate observational data, further highlighting the need for observational efforts and close collaboration between field scientists and modelers.

The more detailed simulation of permafrost degradation trajectory with a sub-grid representation of excess ice also builds more potential on better modeling the permafrost-carbon feedback with biogeochemistry activated (CLM5BGC). Excess ice stabilizes the permafrost thermal regime, therefore alter the rate of carbon releasing from the permafrost (Shuur et al., 2008). Improved projections of permafrost warming could also enhance modeling of vegetation type changes (e.g. shrub expansion) that determines the nitrogen uptake to the atmosphere (Loranty and Goetz, 2012). On the other hand, the possibility to simulate surface subsidence and excess ice meltwater formation also opens the possibility of a more accurate representation of wetland formation. The increase in the area of wetland and soil moisture have an impact of the balance of CH_4 and CO_2 releasing from the permafrost as more organic matter could decompose in an anaerobic pathway (Lawrence et al., 2015; Treat et al., 2015). Compared to the parameterized inundated area simulation in the CLM5 (Ekici et al., 2019), a process-based wetland physics scheme together with the sub-grid representation of excess ice in this study would substantially contribute to the biogeochemical modeling over the circum-arctic area.

5. Conclusion

This study develops a sub-grid representation of excess ice in the CLM5 and examines the impacts of the existence and melting of excess ice in the sub-grid scale in a warming climate. Extra landunits duplicated from the natural vegetated landunit in the CLM sub-grid hierarchy make it possible to prescribe up to three different excess ice conditions in each grid point with permafrost.

A test over the Lena river delta showcases that the sub-grid representation of excess ice can retrieve the sub-grid variability of annual thaw-freeze state and the excess ice melt/surface subsidence through time. On the other hand, initializing excess ice homogeneously throughout the grid cell produces a smaller stabilization effect of excess ice to the permafrost thermal regime and the local surface subsidence under a warming climate. With a tiling scheme ingesting a global data set of excess ice condition into the CLM surface data, our model development shows the capability of portraying more details on simulating permafrost degradation trajectories. As excess ice thermally stabilizes the permafrost on the sub-grid scale, permafrost degrades with a trajectory from continuous permafrost to discontinuous permafrost, and finally to a permafrost-free area. The modeled global pattern of permafrost therefore exhibits regions of discontinuous permafrost as the transition zone between the continuous permafrost and degraded permafrost.

This study, for the first time, used an ESM to project excess ice melt/surface subsidence and permafrost degradation with sub-grid variability. The approach of duplicating tiles at the landunit level instead of the column level allows more freedom for further developments in this direction. Furthermore, the new CLM tiling hierarchy has much more potential than representing more accurate excess ice physics as examined in this study. Further advancing the excess ice modeling relies on additional observational studies/datasets of the excess ground ice conditions on a global scale. The model development in our study, therefore, lays the foundation for further

advances focusing on excess ice modeling and other processes in the CLM framework that could benefit from an improved sub-grid representation.

Code/Data Availability

The original Community Land Model is available at https://github.com/ESCOMP/ctsm. The source code of model development in this study is available from the corresponding author upon request.

Author contributions

L.C conducted model development work and wrote the initial draft with additional contributions from all authors. H.L, S.W, and K.S.A provided ideas and help during the process of model development. H.L provided the code of excess ice physics in the earlier version of CLM. L.C prepared all figures.

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Table 1: The excess ice initialization scenario in each of the three terraces (landunits) for the Lena River delta, as well as that for the single-landunit excess ice initialization case.

Depth (after adding ice)	Volumetric Ice content	Area weight
No excess ice terrain		
N/A	0%	24.6%
Holocene ground ice terrain		
0.9-9 m	65%	66.6%
Yedoma ice complex		
0.6-20 m	90%	8.8%
Average ice single-landunit case		
0.6-0.9 m	7.92%	100%
0.9-9 m	51.21%	100%
9-20 m	7.92%	100%

Table 2: The tiling scheme prescribing area weights of landunits for each CAPS class. The detailed CAPS classes are shown in Figure 2.

Overall visible ground ice content for each CAPS point	Tiling scheme (area weights for each excess ice category)	Eligible CAPS types
5%	80% no excess ice; 20% Low	clf; clf; slf; ilf; clr; dlr; slr; ilr
15%	58% no excess ice; 20% Low; 22% Medium	cmf; dmf; smf; imf; dhr; shr; ihr
15%	66% no excess ice; 20% Low; 14% High	chr
25%	44% no excess ice; 20% Low; 22% Medium; 14% High	dhf; shf; ihf
25%	52% no excess ice; 20% Low; 28% High	chf

Note: For each class, the first letter is for the permafrost extent, the second for the excess ice content, and the third for the terrain and overburden, following Brown et al. (2002).

Table 3: List of simulations conducted for this study.

Cases	Description
	Single point cases for the Lena river delta
Triple-landunit case	Applying the sub-grid representation of excess ice. Three natural vegetated landunit initialized.
Average ice single-landunit case	Not applying the sub-grid representation of excess ice. Only one natural vegetated landunit initialized. The grid-mean excess ice content for each soil layer in the only landunit is calculated by spatially averaging those in different landunits in the triple-landunit case.
	Global simulation cases
No ice case	Not adding any excess ground ice (the original CLM5 simulation).
Sub-grid ice case	Applying the sub-grid representation of excess ice. A tiling scheme helps to "translate" excess ice conditions in the CAPS data to fit what the CLM5 requires.
Grid-average ice case	Not applying the sub-grid representation of excess ice. The grid-mean excess ice content for each soil layer is calculated by spatially averaging those in different landunits in the sub-grid ice case.

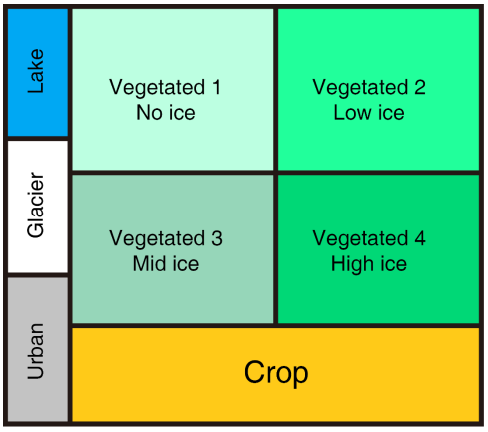
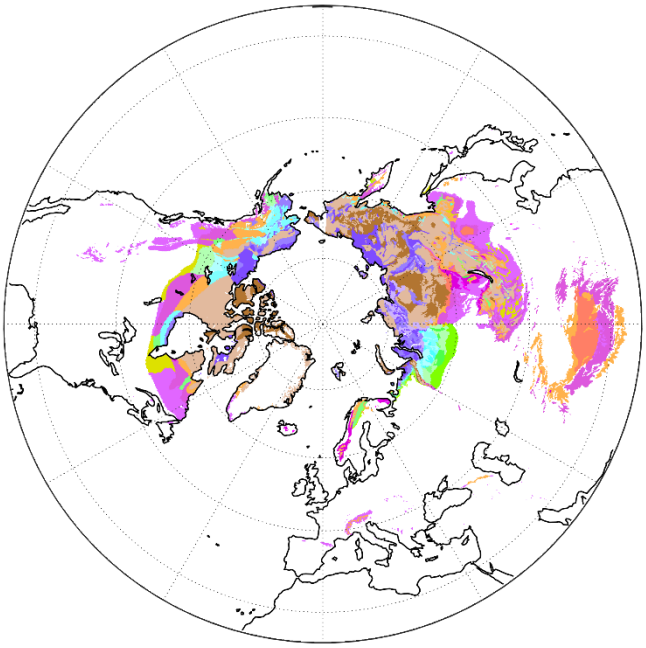


Figure 1: Modification of the CLM5 tiling hierarchy on the landunit level containing four natural vegetated landunits for different excess ice conditions.



Permafrost area classification

Permafrost Extent	Ground Ice Content (percent by volume)				
	Lowlands, highlands, and intra-and intermontane depressions			Mountains, highlands, ridges, and plateaus	
	25%	15%	5%	15%	5%
Continous (100%)	chf	cmf	clf	chr	clr
Discontinous (70%)	dhf	dmf	dlf	dhr	dlr
Sporadic (30%)	shf	smf	slf	shr	slr
Isolated (5%)	ihf	imf	ilf	ihr	ilr

* Letter code naming: The first letter is for the permafrost extent, second for the ground excess ice concent, and the thrid for the terrain and overburden.

Figure 2: Spatial distribution of excess ground ice in the Northern Hemisphere modified from Brown et al. (2002). Compared to the original data, permafrost extents and ground ice contents are converted to definite numbers (percentages) for model computation.

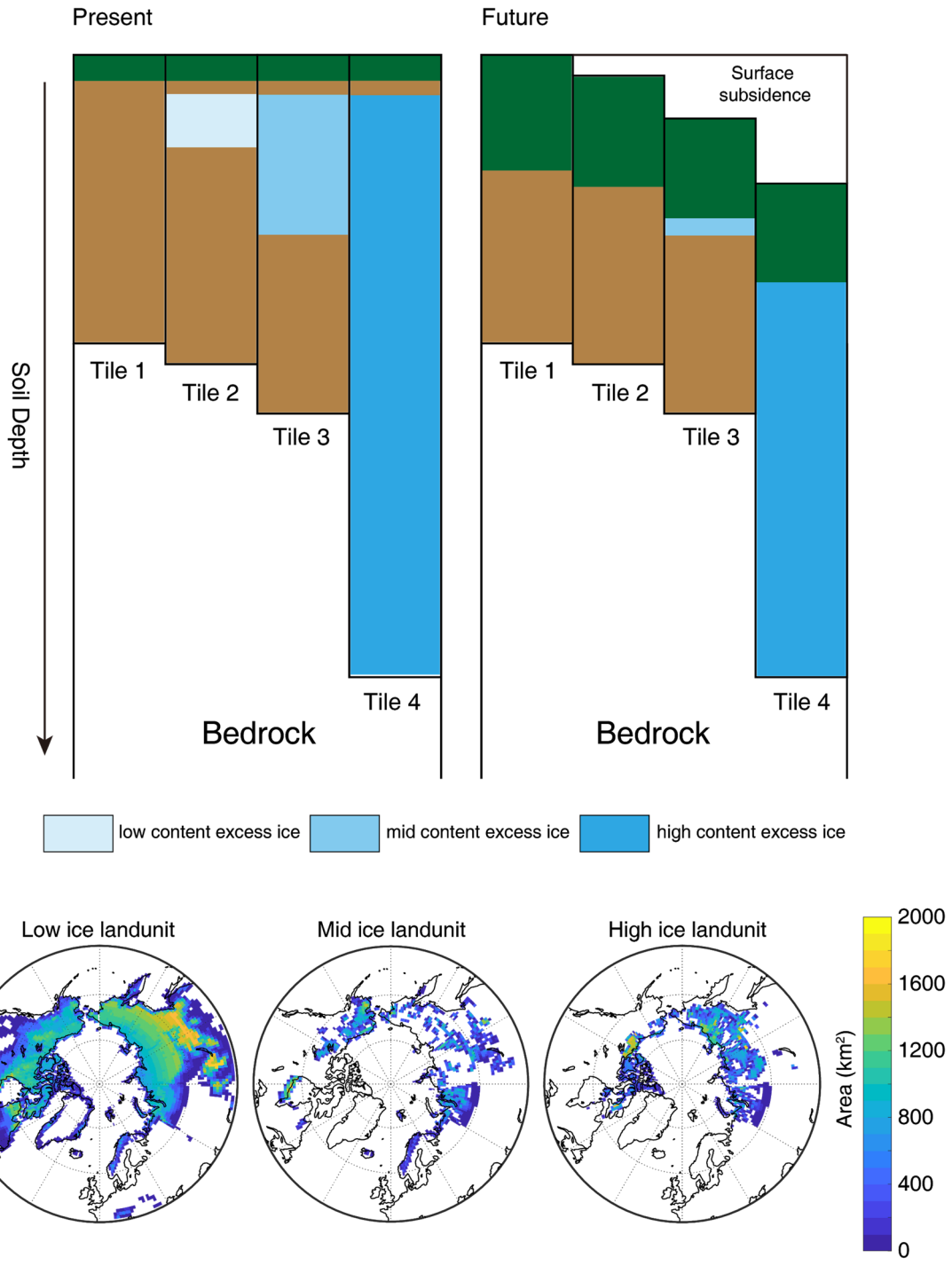
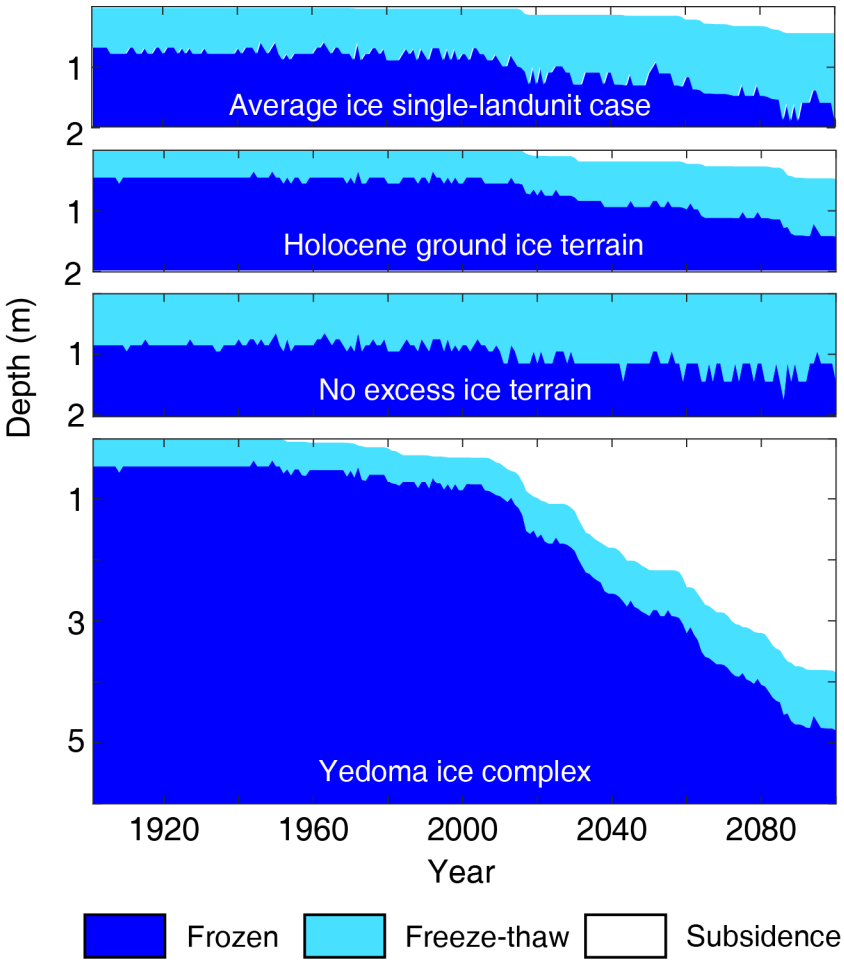


Figure 3. Schematic representation of the sub-grid excess ice initialization scenario, and maps showing the area occupied by different excess ice landunits, i.e. the initial condition of excess ice in the global simulation.



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1243 **Figure 4. Annual freeze-thaw state for the three terraces for the triple-landunit case, as well as for the**
1244 **average ice single-landunit case.**

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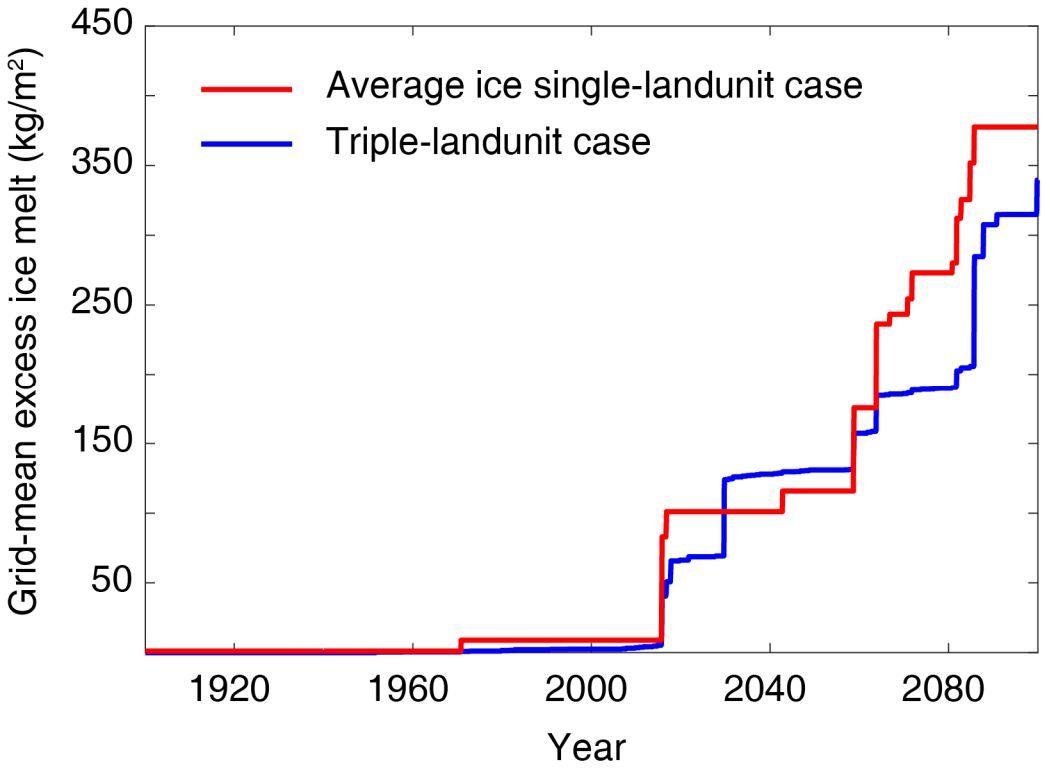

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1247 **Figure 5. Grid-mean excess ice melt since 1900 for the single-point cases over the Lena river delta with and**
1248 **without the sub-grid excess ice initialization.**

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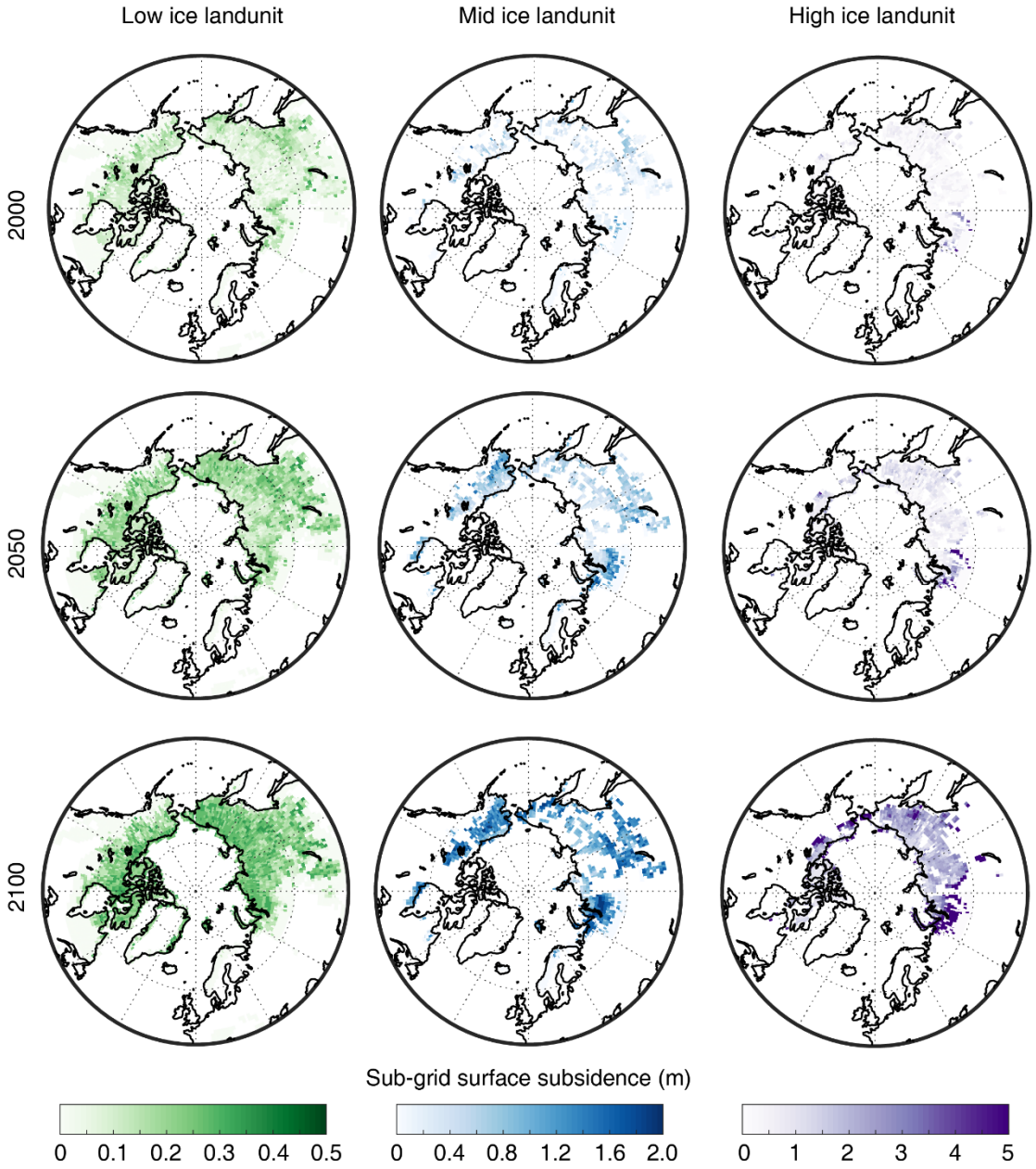

Figure 6. Maps showing sub-grid surface subsidence (m) in 2000, 2050, 2100 in the low, mid, and high excess ice landunits in the sub-grid ice case.

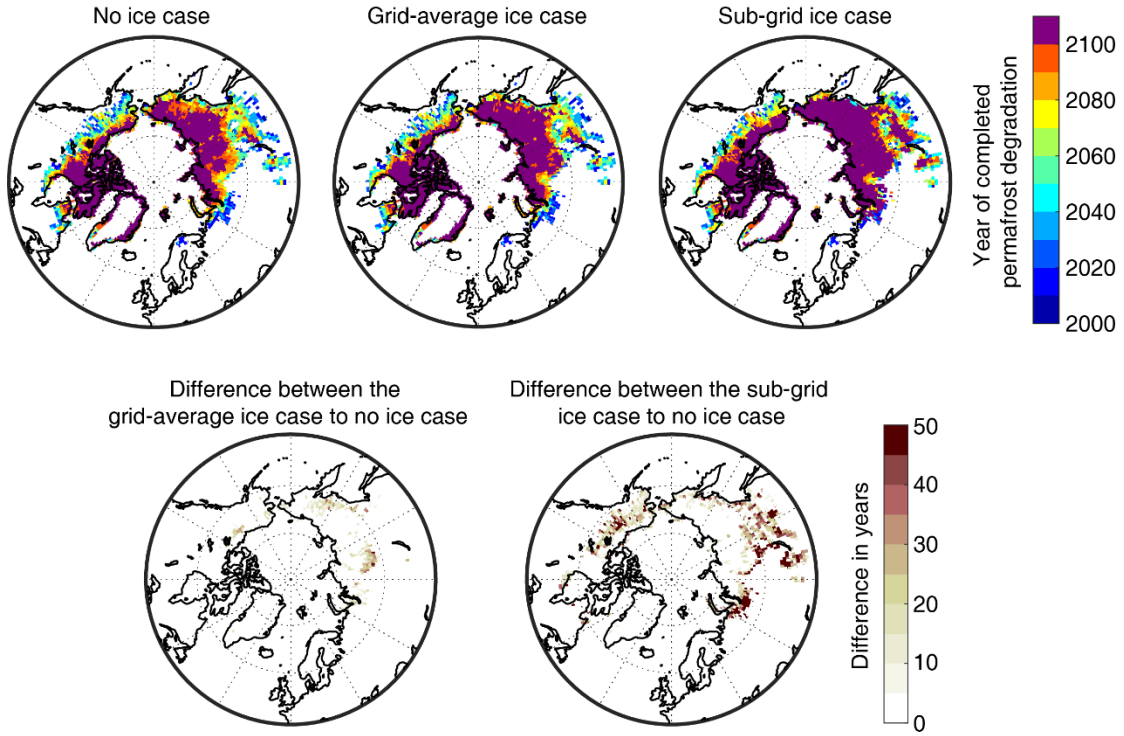

Figure 7. Maps showing the year of completed permafrost degradation (upper set of three maps), as well as the differences between cases (lower set of two maps). The purple color indicates the existence of permafrost in these grid points by 2100. The difference in years is provided only for grid cell with completed permafrost degradation before 2100.

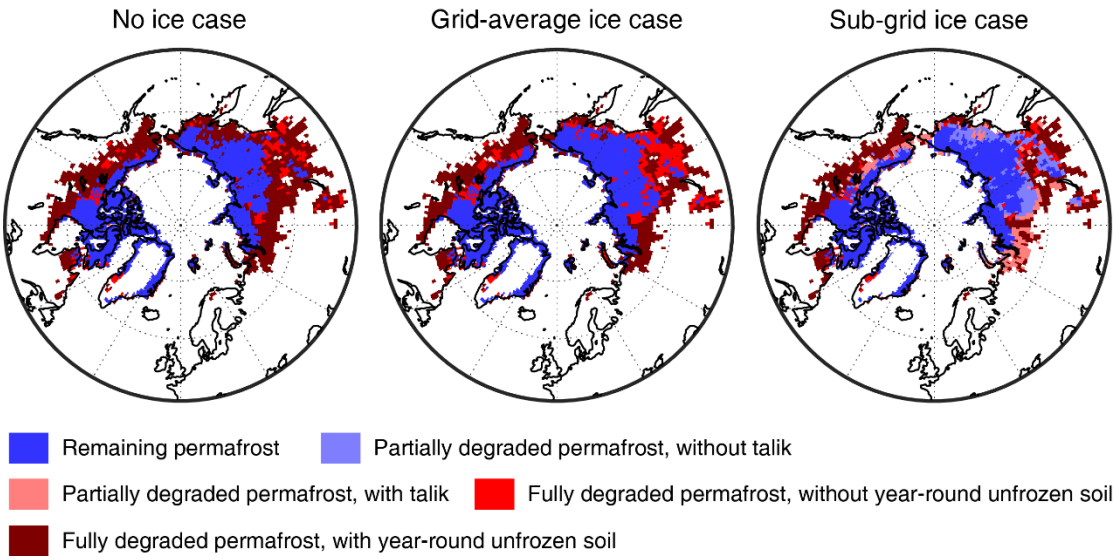

Figure 8. Maps of different stages of permafrost degradation diagnosed from the model output by the year 2100.

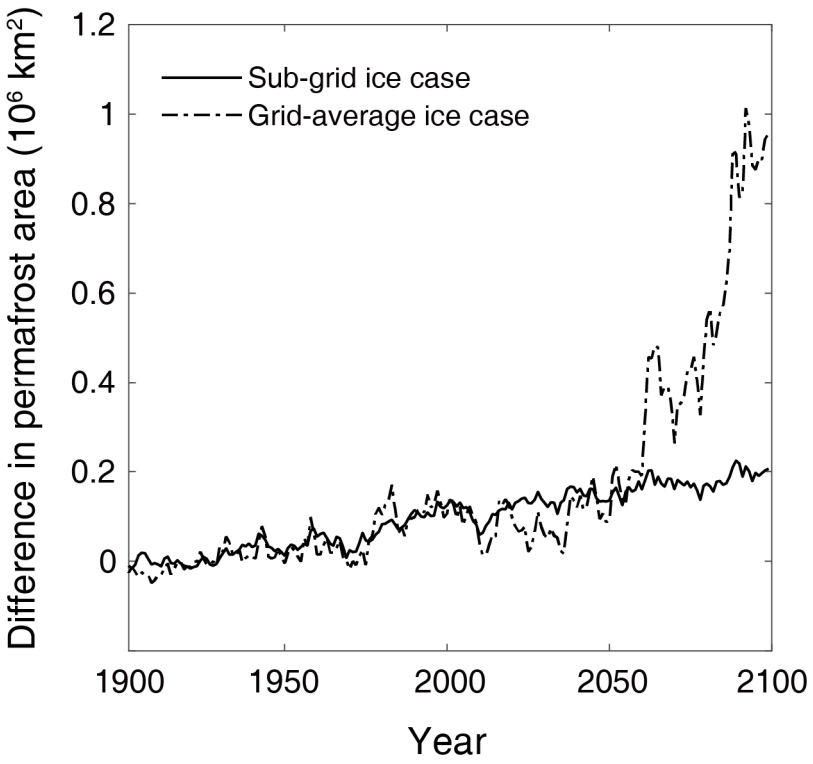

Figure 9. Difference in modeled permafrost area vs. time between the sub-grid ice case and no ice case, as well as between the grid-average ice case and no ice case.