Letter to the editor

We would like to thank both reviewers for their thoughtful suggestions and the editor for handling our manuscript. We prepared a revised version in which we addressed all comments of both reviewers. Here, we give an overview of the main changes to our manuscript, as well as a point-to-point reply with line numbers referring to the revised manuscript.

Main changes to the manuscript

1. Reviewer 2: We modified Figure 1 as suggested by the reviewer.

2. Reviewer 3: We extended a paragraph in Sect. 4.4 (Comparison to in situ observations of ground ice) and added a new paragraph in Sect. 4.5 (Limitations) to discuss the modelling of ice segregation during permafrost formation.

3. Reviewer 3: We included the suggested references.

Response to anonymous referee 2

We would like to thank the reviewer for evaluating our answers to the review and accepting the majority of our revisions. In the following, we provide a reply to the remaining points discussed by the reviewer as well as changes in the manuscript.

The comments of the reviewer are written in **bold**, the extracts of the manuscript in *italics* with changes highlighted in blue and line numbers referring to the revised manuscript.

I am happy with most of the revisions made. Although I have one comment about the schematic in Figure 1. Why is the top of the segregated ice flat (visually that's what it appears)? Conceptually, the surface topography should follow the topography of the segregated ice (see, for example, Figure 2 at https://tc.copernicus.org/articles/13/97/2019/)

We thank the reviewer for the feedback. We changed the figure so that the surface topography follows the topography of the segregated ice. Furthermore, it shows the formation of segregated ice at the base of the permafrost, which was suggested by another reviewer.

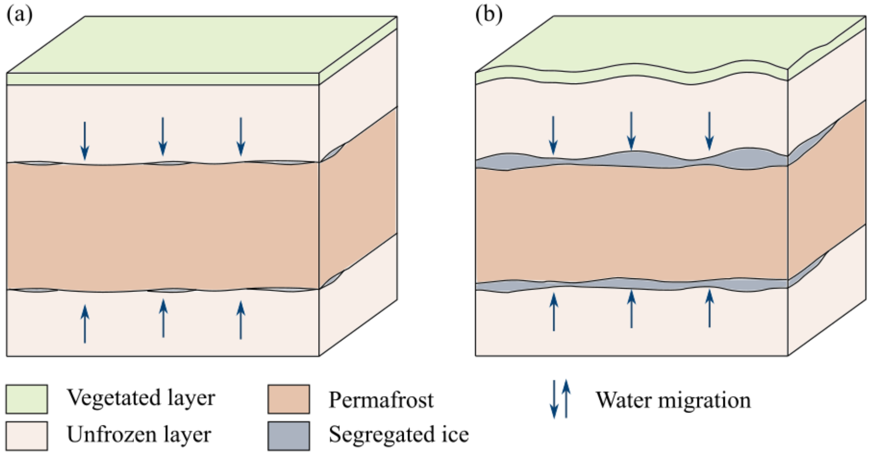

Figure 1. Illustration of ground heave through ice segregation at the top and the base of the permafrost. (a) Lenses of segregated ice are formed. (b) If the segregated ice is preserved over a long time period, layers with segregated (excess) ice are forming, causing heave of the ground surface. Figure modified after Fu et al. (2022).

Response to anonymous referee 3

We would like to thank the reviewer for evaluating our manuscript and for the useful comments, which helped to improve it. In the following, we provide a reply to the points discussed by the reviewer as well as changes in the manuscript.

The comments of the reviewer are written in **bold**, the extracts of the manuscript in *italics* with changes highlighted in blue and line numbers referring to the revised manuscript.

The manuscript submitted by Aga et al. describes the application of the CryoGrid model to simulate ice segregation and thaw consolidation in permafrost. An important factor in determining the impact of warming in permafrost environments is the ground ice content. Efforts to improve the assessment of ground ice content can therefore improve predictions of the impacts of climate change. While the model described in the MS makes some progress in this respect, it appears to be largely limited to segregated ice formation in the upper part of the permafrost, i.e. the transient layer. My main concern with the MS appears to be similar to the point raised by Reviewer 2 that the authors consider a relatively short period and formation of 2-3 cm of segregated ice and do not consider the greater accumulations of ice that formed over longer time periods which would make sense given this is a modelling paper focussing on ice segregation and thaw consolidation. Although the authors refer to scenarios with a spin-up of 1000 years it isn't clear to me they have adequately addressed the concern given the spin up refers to 10-year period repeated several times rather than consideration of the historical climate. My main concern with the MS is the authors do not seem to consider ice segregation that occurred as permafrost formed. In areas that were glaciated in North America for example, permafrost largely formed in the glacial sediments after the glaciers receded so relatively young permafrost exists (the age depending on the effect of subsequent warm and cold periods during the Holocene). Ice segregation would have occurred at the base of the permafrost as freezing progressed, until the ice accumulation was unable to overcome the effective stress. This results in large ice accumulations at depth in the fine-grained glacial and glacial lacustrine sediments for example (to depths of 5-10 m or deeper and not necessarily related to ongoing sedimentation) – see for example, Gaanderse et al. (2018); Wolfe and Morse (2017); Smith et al. (2007). From what I can tell the model does not consider this accumulation of ice which is important to consider in assessments of the impact of warming. This would appear to be a rather important limitation to this model.

We agree with the reviewer that the ground ice distribution in epigenetic permafrost is not only controlled by the conditions of the last 100 to 1000 of years, but by the evolution of the conditions since the permafrost formed. However, we focus on syngenetic permafrost in this study, assuming frozen conditions at the beginning of the simulation and taking into account sedimentation. This allows us to simulate the ground ice distribution in the uppermost soil layers.

Our model would be in theory also capable of simulating epigenetic permafrost, assuming unfrozen conditions at the beginning. All necessary processes are implemented in the model code to simulate not only ice segregation at the top of the permafrost but also at the base of the advancing freeze front, as suggested by the reviewer. However, this functionality is currently restricted by several factors as discussed in Sect. 4.4: Preparing bias-free forcing data over such long time periods is challenging and beyond the scope of this work. The sedimentation regime including sedimentation rate and type of deposited material would be necessary in case sedimentation occurs at the field site. Furthermore, 3D effects need to be considered such as lateral water fluxes and potential non-horizontal freeze fronts (as occurring during palsa formation). These points limit the possibility to apply the model to epigenetic permafrost, even though the model could perform such simulations. This would be an interesting aspect for future studies.

We included clarifications in the discussion of our manuscript and added a paragraph in the section about limitations.

Line 681 ff.: *Nevertheless, the comparison to observed ground ice contents suggests that our model (with the simplified stratigraphy) is capable of modelling ice segregation in the correct order of magnitude at both the Bayelva field site and Samoylov island. However, we see three main limitations of our model setup which need to be addressed to simulate more realistic cryostratigraphies: (i) the climate data used for spin-up, (ii) the constant sedimentation regime and (iii) the hydrological regime. Overcoming these challenges would allow us to simulate the ground ice evolution since the formation of permafrost, including ice segregation at the permafrost base. This would enable to resolve the ground ice distribution also in greater depths in the soil column, e.g. the ice accumulations in glacial and lacustrine sediments (Gaanderse et al., 2018; Smith et al., 2007; Wolfe and Morse, 2017).*

Line 747 ff.: *In this study, we run the model for syngenetic permafrost, i.e. assuming frozen conditions at the beginning of the simulation and simulating the evolution under a sedimentation regime. Like this, the ground ice distribution in the uppermost parts can be obtained. The ground ice in deeper soil layer could be modelled in principle with an extended spin-up period. In contrast to that, epigenetic permafrost could be simulated through a model setup with unfrozen conditions at the beginning. In this case, ground ice would likely be formed at the top of the permafrost and at the base of the advancing freeze front, but three-dimensional effects such as lateral water fluxes and non-horizontal freeze fronts might play a major role and are not accounted for in the current model. Furthermore, both for syngenetic and epigenetic permafrost, plaeo-climate data to force the model (and potentially information on the sedimentation regime) are required to obtain realistic ground ice distributions (Sect. 4.4).*

Several conclusions presented were not unknown including the influence of various factors on formation of segregation ice. It has been well known for decades that soil type is important and that ice accumulation is greater in fine-grained material and peat (e.g. Konrad and Morgenstern 1983; Williams and Smith 1989). This is based on field evidence and lab experiments. There was quite a bit of research done on ice segregation and frost heave 30-50 years ago including model development so a great deal of literature exists including that generated by engineers but there appears to be limited consideration of this body of work. This includes the large body of work by RD Miller, as well as Konrad

and Morgenstern (1980,1981, 1982 a,b, 1983), O'Neill (1983); Nixon (1991) and others mentioned in the comments below (see also ref list).

We agree with the reviewer that influencing factors on ice segregation and thaw consolidation are known from earlier work. This model includes these processes in the framework of a land surface model, allowing a simulation in dependency on changing climatic conditions. To avoid misunderstandings, we changed the wording in the introduction (research objectives) and the conclusions as suggested by the reviewer. Please refer to comments below.

We see the point that our manuscript can benefit from more references on earlier work. We included the suggested references in the manuscript. Please refer to the comments below.

L5 – revision suggested: "...capable of simulating segregated ice formation..."

We changed the wording as suggested.

Line 4 ff.: *In this study, we present a model scheme, capable of simulating segregated ice formation during a model spin-up together with associated ground heave.*

L29-30 Note O'Neill et al. (2019) only considered 3 ice types in their model but there are others including injection ice. Reference could be made to the IPA glossary, French (2017) or French and Shur (2010).

We included injection ice in the manuscript.

Line 29 ff.: *Ground ice can be present as pore ice or excess ice, which can occur as relict ice, wedge ice, segregated ice or injection ice (French and Schur, 2010; French, 2017).*

L45-46 – There is also field evidence of segregated ice in this type of material, such as information collected from geotechnical boreholes, e.g. , Gaanderse et al. (2018); Wolfe and Morse (2017); Smith et al. (2007).

We added the information and included the references.

Line 45 ff.: *O'Neill et al. (2019) modelled the occurrence of segregated ice in Canada, showing abundance in fine-grained lacustrine sediments, raised peat plateaus and uplifted marine sediments. This distribution is supported by borehole information and field studies (Gaanderse et al., 2018; Smith et al., 2007; Wolfe and Morse, 2017).*

L52-53 – This is confusing as the formation of ice releases latent heat which would delay freezing. The effect of latent heat release reduces cooling of the active layer in fall/winter (e.g. Riseborough and Smith (1998).

Ground ice formation releases latent heat, delaying the freezing. In contrast, the thaw of ground ice consumes energy, delaying the permafrost thaw. This is supported by the study of Riseborough (1990). We clarified this in the manuscript.

Line 51 ff.: *The ground ice content and its distribution strongly determines the sensitivity of permafrost to thaw (Jorgenson et al., 2010; Nitzbon et al., 2019). Ground ice formation releases latent heat, delaying the freezing. In contrast, ice-rich layers in the soil can delay permafrost degradation as energy is consumed upon melting of the ground ice, which is consequently not available for the warming of the ground (Riseborough, 1990).*

Figure 1 – There is also upward migration of water towards the freezing front at the base of permafrost as it aggrades.

We changed the figure accordingly.

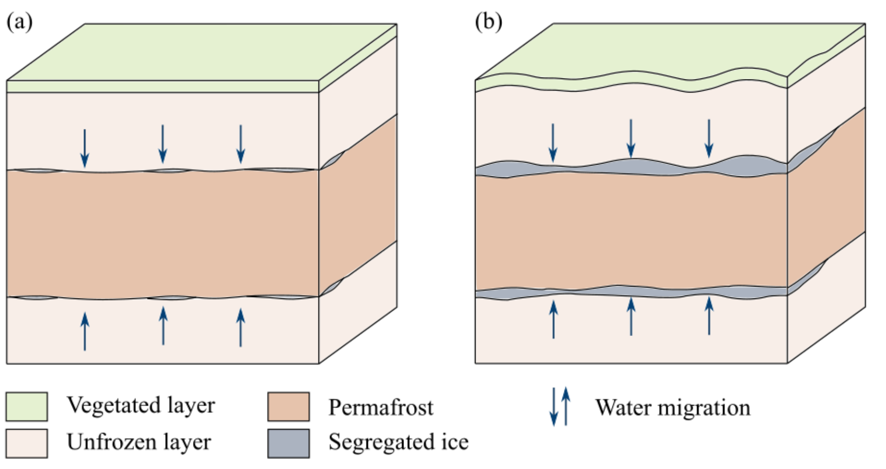

Figure 1. Illustration of ground heave through ice segregation at the top and the base of the permafrost. (b) If the segregated ice is preserved over a long time period, layers with segregated (excess) ice are forming, causing heave of the ground surface. Figure modified after Fu et al. (2022).

L69-72 – As mentioned above there has been much earlier work done with respect to modelling frost heave (e.g. papers by Konrad and Morgenstern; Nixon 1991 etc.)

We included the suggested references in the manuscript.

Line 70 ff.: *Thaw consolidation has been the focus of model development for many decades (Morgenstern and Nixon, 1971; Nixon and Morgenstern, 1973; Sykes et al., 1974; Konrad and Morgenstern, 1980, 1981, 1982a, b; Konrad, 1983; O'Neill, 1983; Nixon, 1991; Foriero and Ladanyi, 1995; Dumais and Konrad, 2018)...*

L75-78 – See previous comment regarding issue of latent heat release.

We changed the introduction as described in the comment above. Here, we formulated the sentence in a way that could be misunderstood. We changed the formulation.

Line 78 ff.: *Furthermore, as ice segregation is not implemented, they neglect the delay in permafrost warming through the thaw of segregated ice layers, formed during the simulation period.*

L78 – Revision suggested: "...ground can be simulated with..."

We changed the wording as suggested.

Line 80 ff.: *In this study, we demonstrate that segregated ice in the ground can be simulated with a climate-dependent spin-up procedure, which aims at reproducing the evolution of ground ice stocks.*

L88 – See early comment regarding the fact that the role of these factors was not unknown. Isn't it more correct to say that you evaluate the ability of the model to adequately represent these relationships.

We changed the wording in the manuscript.

Line 89 ff.: *We evaluate the performance of our model to reproduce known controlling factors on ice segregation and thaw consolidation. Particularly, we analyze different climatic conditions (by applying different forcing data sets), the soil type (by using different grain sizes and compositions) and external loads.*

L117 – There was much earlier work regarding freezing characteristic curves. See examples in Williams and Smith (1989) and also Horiguchi and Miller (1983) and others.

We agree with the reviewer that there was earlier work on freezing characteristic curves. However, this is the methods section and we describe here on which work our model is based. To include earlier work would confuse the reader in our opinion. Therefore, we decided to not include this literature in the manuscript.

237-238. There is earlier literature regarding hydraulic conductivity in freezing soils, see examples and figures in Williams and Smith (1989), Horiguchi and Miller (1983), Burt and Williams (1976), Perfect and Williams (1980).

We added references to the manuscript.

Line 240 ff.: *When the soil freezes, water fluxes are significantly smaller than in unfrozen conditions due to reduced liquid water contents and hydraulic conductivity (Burt and Williams, 1976; Horiguchi, 1983). However, the remaining soil water is still partly mobile. This is mainly driven by matric potentials, which reach considerably negative values for ground temperatures below zero degrees, resulting in an attraction of soil water towards the freezing front (Perfect and Williams, 1980; Williams and Smith, 1989).*

L248 – Essentially you are only considering one type of excess ice, i.e. segregated ice.

We agree with the reviewer, that segregated ice is a type of excess ice. At this point in the manuscript, we want to emphasize that also the definition within the model framework is differently. We clarified this in the text.

Line 252 ff.: *We highlight that the term "segregated ice" is defined differently within the framework of the CryoGrid community model than the term "excess ice" in previous versions of the model.*

L255-256 – Formation of other types of ice are associated with different process eg. Thermal contraction cracking required for ice wedge formation.

We added this information in the manuscript.

Line 259 ff.: *We note that the new model scheme can only represent segregated ice and that the formation of other forms of excess ice such as wedge ice cannot be accounted for as they are associated with different processes during formation.*

L272 – As mentioned in general comments, these examples aren't necessarily representative of conditions everywhere with respect to climate and geological history.

This is a proof-of-concept study to evaluate the performance of the newly developed model scheme. We discuss the challenges regarding the historical climate data in Sect. 4.4 and extended it according to the first comment of the reviewer. Furthermore, we added a paragraph in the section about limitations. Please see the answer to the first comment of the reviewer.

L326-327 – The model seems to assume that frozen conditions at depth already exist but there is no simulation of the formation of segregated ice as the permafrost initially formed.

It is currently not possible to simulate the conditions during permafrost formation. This is not because of the presented model scheme but due to the lacking historical forcing data. To prepare such forcing data is a big challenge and out of the scope of this study. We extended parts of the discussion and the section about limitations. Please see the answer to the first comment of the reviewer.

L481 – revise to "thicker active layer" or "deeper permafrost table"

We changed the wording.

Line 484 ff.: *Despite less ice segregation, the ground heave is more pronounced in Bayelva during the spin-up, due to wetter conditions and a deeper permafrost table, resulting in stronger soil swelling.*

L485 – The water migration is dependent on the temperature gradient and thermal conditions will also affect the hydraulic conductivity (see refs provided earlier).

We added this information in the manuscript and added the suggested references.

Line 488 ff.: *Varying the climatic forcing shows, that the model results depend on both soil moisture and temperature gradients in the ground, controlling the water migration towards the freezing front (Burt and Williams, 1976; Perfect and Williams, 1980).*

L486-505 – As mentioned in general comments, the role of material type in ice segregation was not unknown and is a key consideration in determinations of frost susceptibility or segregation potential (see papers by Konrad and Morgenstern). There is also much field evidence of occurrence segregated ice in fine-grained soils (see refs in general comments) and permafrost maps showing ground ice content including the circumpolar IPA map or O'Neill et al. (2019) base the

ice content on material type.

We agree with the reviewer that this was known from earlier studies. Here, we aim to represent these processes in our model. Therefore, we changed the wording in our research objectives.

Line 89 ff.: *We evaluate the performance of our model to reproduce known controlling factors on ice segregation and thaw consolidation. Particularly, we analyze different climatic conditions (by applying different forcing data sets), the soil type (by using different grain sizes and compositions) and external loads.*

L506-517 – Others have considered role of loading on segregation process e.g. Konrad and Morgenstern (1983).

We added the suggested reference in the manuscript.

Line 512 ff.: *Applying an external load influences the formation and thaw of segregated ice (Konrad, 1983, Fig. 12).*

L561 – As mentioned in earlier comments the consideration of fixed amount of excess ice at the beginning of the simulation is an important limitation of the model. There is no consideration of formation of segregated ice as the freezing front progresses into the soil as permafrost forms.

While the model is capable of simulating the conditions during permafrost formation, including ice segregation as the freezing front progresses into the soil, we cannot do any model simulations for this scenario yet due to lacking historical forcing data. We extended parts of the discussion and the section about limitations. Please see the answer on the first reviewer comment.

L693 – There were many of these experiments at bench and field scale in the past and reported in engineering literature (Konrad and Morgenstern papers cited above may include some) and there is also work done by the Geotechnical Science Laboratory at Carleton University in the 1980s and 1990s both bench scale and field scale at facility in Caen (some eg. Smith and Onysko; Williams and Wood 1985; Compendium of reports related to Caen facility, i.e. Canada-France ground freezing expt. can be found in Smith and Burgess 2007).

We included more references in the manuscript.

Line 701 ff.: *Another possibility for validation could be laboratory freezing experiments. An example is the study by Xue et al. (2021), who conducted a one-sided freezing experiment in saturated soil to investigate the relationship of matric potential, unfrozen water content and segregated ice. Further experiments have been presented by Konrad and Morgenstern (1980, 1981,* *1982a, b);Smith and Onysko (1990); Williams and Wood (1985).*

L700 – See earlier comment regarding lack of consideration of ice accumulation at permafrost base as permafrost forms.

Such simulations would require bias-free historical forcing data and information about the sedimentation regime. We extended parts of the discussion and the section about limitations. Please see the answer to the first comment of the reviewer.

L724 – There was earlier literature on role of creep in segregation processes (might be in some pubs I've already mentioned or in body of work by RD Miller).

We included the reference of Williams and Smith (1989), which was suggested by the reviewer, in the manuscript.

Line 730 ff.: *Creep processes can play an important role in permafrost and can occur at very low slope angles (Williams and Smith, 1989). The soil mechanical processes implemented in the model consider only primary consolidation, and do not account for long-term creep processes, which can be considered to be a first order approximation. For long-term simulations with thick sedimentary deposits near or above thawing temperatures, creep processes should be implemented to get a better representation of the deformation of the soil column.*

L744-747 – Considering this period or other earlier cooling periods would require consideration of formation of permafrost at base of permafrost as the frost front progresses.

This process can be simulated with the model. However, we did not perform simulations including permafrost formation due to lacking paleo-forcing data and information about the sedimentation regime. We extended parts of the discussion and the section about limitations. Please see the answer to the first comment of the reviewer.

L772-778 – See previous comments regarding the fact that most of this was not unknown so we didn't require the model to suggest them. It is more correct to say that you assessed the ability of the model to consider the relationship of these factors to ice segregation.

We agree with the reviewer and changed the manuscript accordingly.

Line 790 ff.: *The model shows that important controlling factors on ice segregation and thaw consolidation can be simulated such as (i) ground temperature gradients and soil water content, (ii) soil type and (iii) external loads.*

References

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We used instead: Riseborough, D.W. (1990): Soil latent heat as a filter of the climate signal in permafrost.

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