Response to anonymous referee 1

We would like to thank the reviewer for the detailed and useful comments, which have helped to improve the quality and readability of our manuscript. 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.

This paper describes a new model scheme, in a suit of the CryoGrid community model (version 1.0. Under review at GMD), to simulate the temporal evolution and the vertical distributions of ground ice content by calculating ice segregation (excess ice) when cold and thaw consolidation when warm, and associated ground heave and subsidence. The model incorporates soil mechanical processes, soil hydrology, and soil freeze/thaw physics. The authors conducted a series of proof-of-concept examinations of the new scheme with respect to climatic (i.e., thermal, and hydrological) conditions, soil types, external loadings, and sedimentation, which demonstrated reasonable performance of the model. It is not so simple to evaluate an additional module when the base model is still under review, however, the reviewer found that the manuscript is moderately well organized and written. Yet, some elaborations and clarifications regarding the points raised below will improve the manuscript before being published in the Cryosphere journal.

The base model is now published and we replaced the reference of the preprint with the published version:

Westermann, S., Ingeman-Nielsen, T., Scheer, J., Aalstad, K., Aga, J., Chaudhary, N., Etzelmüller, B., Filhol, S., Kääb, A., Renette, C., et al.: The CryoGrid community model (version 1.0)–a multi-physics toolbox for climate-driven simulations in the terrestrial cryosphere, Geoscientific Model Development, 16, 2607–2647, https://doi.org/10.5194/gmd-16-2607-2023, 2023.

Ll. 144-146: When it is referred by a general term "soil", is it assumed that the saturation (in terms of volumetric water content?) is equal among the constituents (e.g., mineral, organic)?

The saturation is calculated separately for each grid cell of the soil column and the soil water is distributed equally within the grid cell. In the CryoGrid community model, each grid cell can only consist of one soil type (sand, silt, clay or organic), which cannot be mixed within the gridcell. Consequently, changes in the soil stratigraphy have to be reflected in the grid cell sizes.

Line 165: *To compute the pore water pressure, the buoyancy effect has to be accounted for. For each grid cell of the soil column, which is composed of one soil type (sand, silt, clay or organic), the saturation is calculated separately. When the soil* *is at or near saturation, the porewater results in a reduction of the stress on the soil matrix, as the density of each component is reduced by the density of water.*

L.146: How do you justify the threshold value of 50%? Some reference or practice examples would be helpful.

The threshold of 50 % is an ad hoc assumption for a pragmatic implementation of the buoyancy effect in the code. This is of course a source for uncertainty, so that we included a paragraph in chapter 4.4.

Line 708: *The buoyancy effect reduces the stress on the soil matrix in case the soil is at or close to saturation, while the soil skeleton carries the weight of the overlying soil layers under dry conditions. For a continuous transition, we scale the buoyancy effect between 50 % and 100 % saturation (Sect. 2.1.1). The threshold of 50% is based on an ad-hoc assumption, which should be investigated in more detail in future studies.*

L. 154: Does “grain” refer to mineral only, or include organic matters in the module (or CryoGrid) terminology?

The term "grain" refers to the mineral and organic matter in this context. To avoid confusion, we changed the wording in the manuscript.

Line 176: *The compressibility of a soil can be expressed with a linear relationship between void ratio e [-] (defined as the ratio of pore volume to the volume of mineral and organic matter) and the decadic logarithm of the effective stress $\sigma_z^{'}$ [Pa] (Murthy, 2022) as illustrated in Fig. 3.*

L. 174, l. 211, and l. 454: “section 2.1” is used for a reference, however, section 2.1 includes many subsections. It is more reader-friendly to provide more specific reference (such as at l. 241 “section 2.1.2”).

Line 174: As we are referring to section 2.1, not any of the subsections, it is not possible to refer to a specific subsection.

Line 211: We realized that the reference is unnecessary in this place an deleted it.

Line 454: We changed the reference to the subsection.

Line 514: *As the active layer is saturated with 70-80 %, the compression takes places immediately as described in Sect. 2.1.1 for unsaturated conditions.*

Ll. 205-207: It is not clear how pore water pressure is updated with respect to eqs. (4) and (9).

We improved the clarity in the revised manuscript.

In our model, we calculate excess pore water pressures, while pore water pressures under normal conditions are estimated with the buoyancy effect as described in line 165 ff. As we know the total stress of the overlying soil, we can solve equation 4 for the effective stress of the soil. The value of the effective stress then determines the void ratio (through the compression curve, equation 6), so that the thickness of the grid cell can be calculated.

If the total stress is increased, e.g. by applying an external load, the additional total stress will be taken up completely by the soil water in the first time step. As the effective stress stays unchanged in this time step, we can solve equation 9 for the excess pore water pressure u_e as we know the value for the total stress and the (unchanged) effective stress. The development of excess pore water pressure will result in water fluxes out of the grid cell (equation 10).

When water is flowing out of the affected grid cell, the grid cell looses volume and therefore the thickness d is reduced as described in equation 11. As grid cell thickness d is now known, we can solve equation 8 for the porosity, equation 7 for the void ratio and consequently equation 6 for the effective stress. The effective stress increases and the excess pore water pressure reduces until it reaches a value of zero. In summary, under saturated conditions, we can invert equation 6-8 and update the excess pore water pressure like that.

Line 227: *If the soil is unfrozen and saturated, [...] In these conditions, the effective stress $\sigma_z^{'}$ [Pa] on the soil skeleton can be calculated by reducing the total stress σ_z [Pa] by the pore water pressure u [Pa], as shown in Eq. 4.*

When external loads are applied or sedimentation takes place, the additional stress is taken up by the soil water in a first step, leading to excess pore water pressures u_e [Pa]:

$$u_e = \sigma_z - \sigma_z^{'}, \tag{1}$$

which results in water fluxes j^v_{w,u_e} [$\mathrm{m\,s^{-1}}$] away from the affected grid cell

$$j^v_{w,u_e} = -\frac{K_w}{\rho_w\, g}\left(\frac{\partial u_e}{\partial z}\right). \tag{2}$$

leading to a reduction of the excess pore water pressure by consolidation. The water flux is added to the fluxes calculated based on the Richards equation (Eq. 1). The consolidation continues until the excess pore water pressure reaches a value of zero, while at the same time the effective stress is increased [...]

After calculating the water fluxes in the soil column, the change in water content for each grid cell can be derived. For unsaturated conditions, changing water content is replaced by air. For saturated conditions, no air inflow is possible and changes in water content affect the grid cell size. The thickness of a grid cell d [m] can be calculated for saturated conditions from the volume Θ [$\mathrm{m^3}$] of the grid cell (being the volume of water, ice, mineral, organic) divided by the area A [$\mathrm{m^2}$]:

$$d = (\Theta_w + \Theta_i + \Theta_m + \Theta_o)/A \tag{3}$$

With the thickness of the grid cell d being calculated for saturated conditions directly from the change in water content, we can invert Eq. 8 and Eq. 7 and solve Eq. 6 for the effective stress σ_z' to update the excess pore water pressure with Eq. 9. A reduction/increase in water content results in a change in effective stress and thus in compression/swelling of the soil.

Figure 3: What does the solid straight blue line in the figure (with a filled reverse triangle on the left shoulder) denote? If it explains something it should be noted either in caption or text. Otherwise, should be removed.

The blue line indicates the ground water level. We added some explanation in the figure to clarify.

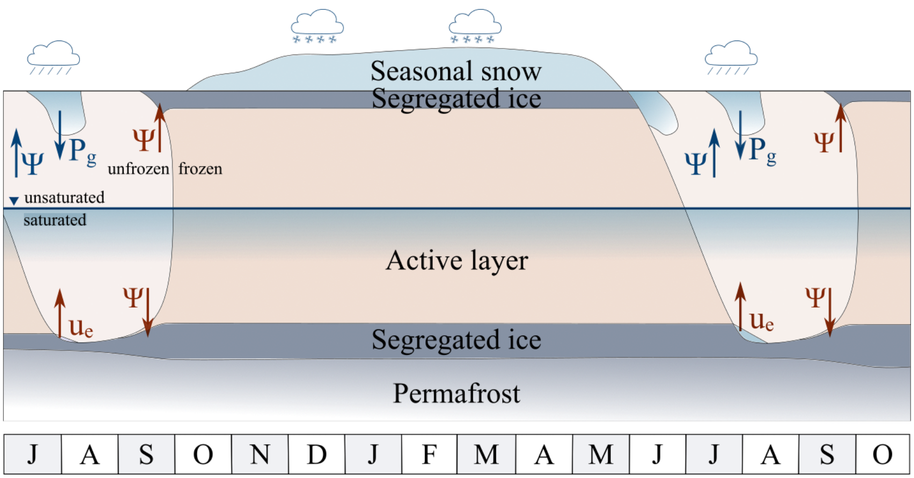


Illustration of the potentials resulting in water fluxes as calculated in the model (not to scale): During winter season, the entire soil column is frozen and no substantial water fluxes occur. When the upper soil layers are unfrozen during summer season, water fluxes in the unsaturated zone are controlled by the gravitational potential P_g and the matric potential ψ. Rainwater or meltwater infiltrates from the top to deeper layers. Most important for ice segregation is the matric potential during fall refreezing (marked in red). In case the downward thawing from the surface during summer reaches (partly) the segregated ice, excess pore water pressures u_e develops, leading to thaw consolidation.

Ll. 257-258, 278: Description of the range of temperature variations and the period of measurement are somewhat awkward. It is assumed to be meant something like "The observed ground temperature at a depth of 20.75 m varied between -9.0 and -7.9 C during the period of 2007 to 2016."

We changed the text in the manuscript.

Line 286: *The observed ground temperature at a depth of 20.75 m increased from -9.0 °C in 2007 to -7.9 °C in 2016 (GTN-P, 2018). With these records, the field site shows one of the strongest warming of permafrost within 123 globally distributed boreholes (Biskaborn et al., 2019).*

Line 309: *Observed ground temperatures at a depth of 9 m varied between -3.0 and -2.6 °C during the period of 2007 to 2016 (GTN-P, 2018) and thus show relatively warm permafrost.*

Ll. 262-263, l. 281: Description is somewhat sloppy. The forcing data should have been taken from “the CCSM4 outputs simulated under the RCP8.5 scenario”, or “the RCP8.5 run by CCSM4”. Why there is no reference on this model or its CMIP5 outputs?

We changed the wording according to the suggestion of the reviewer. Furthermore, we added the necessary references.

Line 291: *The climatic forcing between 1960 and 2012 is derived from the reanalysis product CRU-NCEP (combining data from the Climate Research Unit and National Centers for Environmental Prediction, see Kalnay et al., 1996; Harris et al., 2014), downscaled for Samoylov with in situ data from the automatic weather station. After 2012, the forcing data is taken from the Community Climate System Model CCSM4 outputs simulated under the* Representative Concentration Pathway (RCP) *8.5 scenario (Meehl et al., 2012).*

L. 292: It is not clear the “key difference” from what is discussed.

The key difference in this context is, that we did not assume any excess ice in the beginning of the simulation in contrast to the previous simulation by Nitzbon et al. (2020) and Westermann et al. (2016). We improved the clarity in the manuscript.

Line 324: *For model validation on Samoylov island, we set a soil stratigraphy as described for the center of a low-centred polygon in Holocene deposits in Samoylov in Nitzbon et al. (2020) and Westermann et al. (2016) (multi-layer stratigraphy in Table 3). In contrast to these studies, we did not assume any excess ice in the beginning of the simulation as it is inherently generated by the new model scheme.*

L. 297: Like the above issue, it is not clear from what the upper 0.15 m was unchanged.

We clarified this in the manuscript.

Line 324: *For model validation on Samoylov island, we set a soil stratigraphy as described for the center of a low-centred polygon in Holocene deposits in Samoylov in Nitzbon et al. (2020) and Westermann et al. (2016) (multi-layer stratigraphy in*

Table 3).

Line 329: *To analyze the performance and sensitivity of our model for Bayelva and Samoylov, we used simplified stratigraphies to provide standardized and comparable model setups. Hereby, we use the same soil properties in the upper 0.15 m as in the multi-layer stratigraphy from Samoylov island (see above) to account for the insulating effect of the organic-rich moss layer on top.*

L. 346: it is not so clear what is meant by "the annual downward thawing in summer deepens."

We meant the increasing active layer thickness. We changed the wording in the manuscript.

Line 386: *Further model scenarios include an external load of 5 kPa during the entire simulation (S-clay-load5) and from 1980, when the active layer thickness increases (S-clay-load5-1980).*

L. 361: Is this necessary to mention "that are forced with data from this location"? Any specific reasons?

We deleted the statement from the manuscript.

Line 403: *As the terrain at the field site on Samoylov Island is flat, we set a small gradient of 0.1 m* km^{-1} ~~*for the model runs that are forced with data from this location*~~. *In contrast, the Bayelva field site is situated on gently sloping terrain, so that we increased the gradient to 1 m* km^{-1}.

Table 3. Why is no value given for maximum snow depth in the B-clay scenario? Does this mean snow depth is unlimited?

Yes, the snow depth in the B-clay scenario is unlimited. We added this information in the manuscript.

Line 400: *For the Bayelva field site, we do not set a limit for the snow depth as the accumulation of the snow resulting from the forcing data generally represents local conditions well (Westermann et al., 2023).*

Ll. 401-408: It is difficult to read changes in ground surface height from figures 6, and 1-2 in Supplement B so that it is not easy to follow the statement and discussions. Further, for the sake of reader-friendly discussions on evolution and relative impacts of ground heave (subsidence) and ice segregation (thaw consolidation), it is suggested to plot segregation ice and surface height changes together (possibly overplotted in figures 7, 8, and 10?).

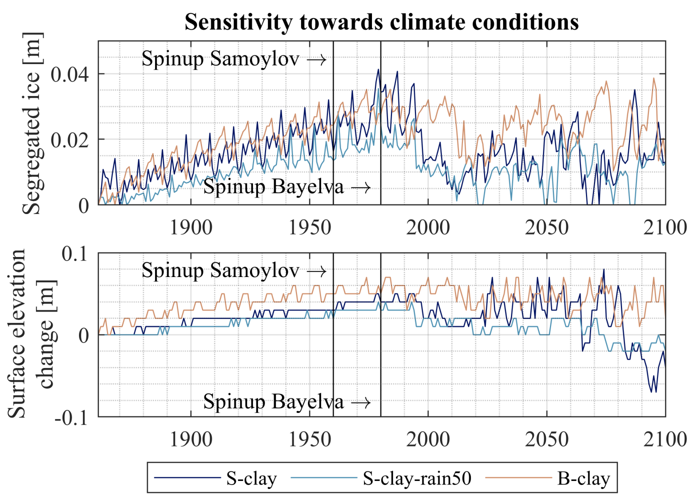
We added plots of the surface elevation changes in figures 7, 8 and 10 (old numbering), as suggested by the reviewer. Furthermore, we extended the result sections with the respective information.

Line 464: *Figure 9 shows the formation of segregated ice and changes in surface elevation for the model runs S-clay (Samoylov forcing data), S-clay-rain50 (Samoylov forcing data with 50 % rainfall) and B-clay (bayelva forcing data).*

Line 466: *The reduction of rainfall in S-clay-rain50 leads to less segregated ice during the spin-up on average with 0.025 m compared to 0.034 in S-clay and consequently less ground heave.*

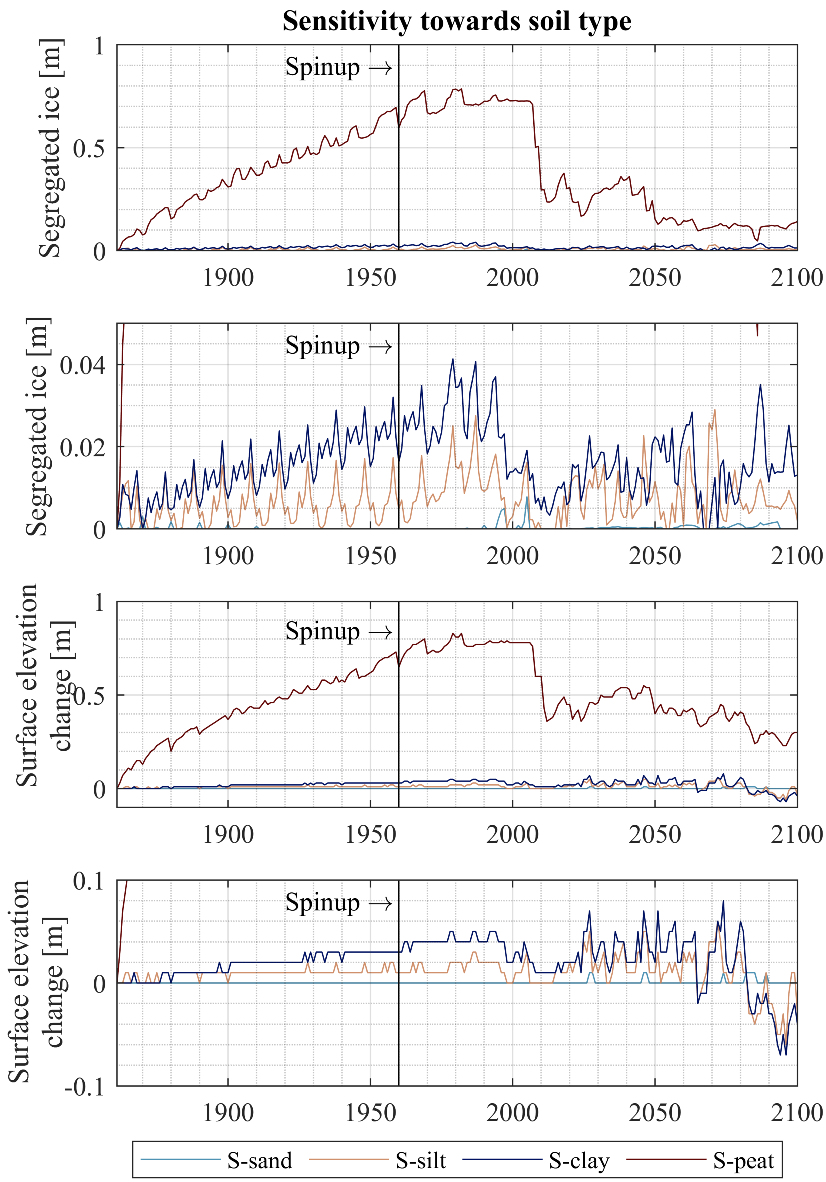
Line 470: *Furthermore, drier conditions lead to less swelling in the active layer, so that fluctuations in surface elevation, especially during the time period 2020-2100, are dampened (Sect. 3.2).*

Line 480: *Despite less ice segregation, the ground heave is more pronounced in Bayelva during the spin-up, due to wetter conditions and a deeper active layer, resulting in stronger soil swelling. During the time period 2020 to 2100, B-clay builds up more segregated ice in deeper soil layers. This can be explained by a slower increase of the active layer thickness compared to Samoylov Island, so that the permafrost table stabilizes for longer time period, enabling new formation of segregated ice. As a consequence, less ground subsidence takes place for the Bayleva run.*

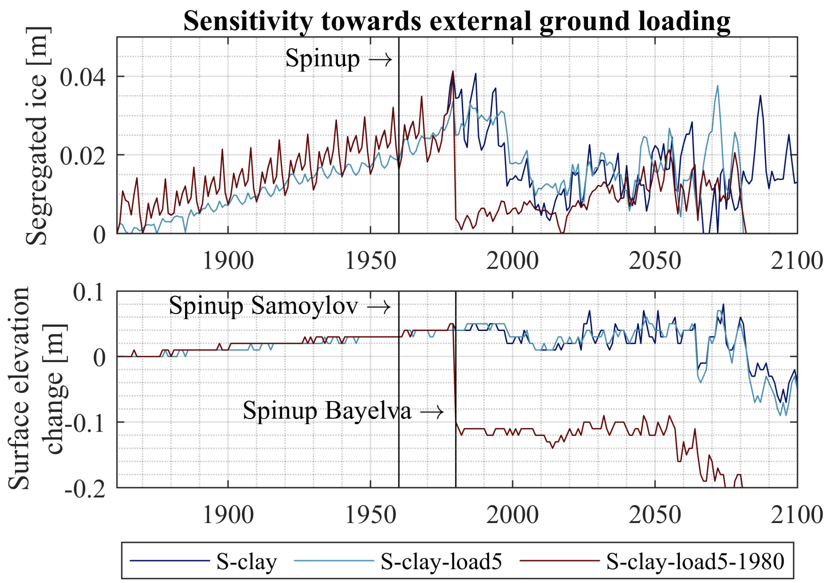


Column-accumulated segregated ice and surface elevation change on the reference date August 31 of each year in the simulation, for the model scenarios S-clay, S-clay-rain50 and B-clay. Drier conditions lead to less formation of segregated ice and thus less ground heave. The moist conditions in B-clay are compensated by smaller temperature gradients in the ground so that similar segregation ice contents are formed during model spin-up.

Line 504: *Soil swelling and shrinking influences the surface elevation, especially during the time period 2020-2100 (Sect. 3.2), but both model scenarios S-clay and S-silt result in a net subsidence of the ground surface.*



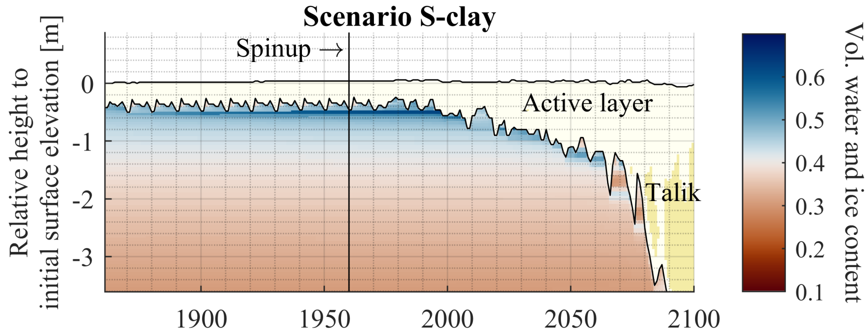
Column-accumulated segregated ice and surface elevation changes on the reference date August 31 for the model scenarios S-sand, S-silt, S-clay and S-peat. With decreasing particle diameter, the soil builds up more segregated ice under equal conditions. Peat soils form substantially more ground ice than mineral soils.



Column-accumulated segregated ice and surface elevation changes on the reference date August 31 for the model scenarios S-clay, S-clay-load5 and S-clay-load5-1980. A load that is acting on the soil column from the beginning of the simulation (S-clay-load5) suppresses ice segregation. A load that is added during thaw consolidation (S-clay-load5-1980) accelerates the process and the ground surface subsides faster.

Figures 6, 9, 11 and 1-4 in Supplement B: The vertical axis of altitude seems to be the model surface height (say, absolute altitude). Unless it is necessary (e.g., in laterally coupled cases), it would be easy to follow the height changes if shown by a relative height with reference to the initial surface altitude. Also, the near-surface zones such as active layer is very small, leading it difficult to read and compare especially for the argument of thermal gradients (e.g., ll. 401-408, ll. 420-425). Elaborations will be very helpful.

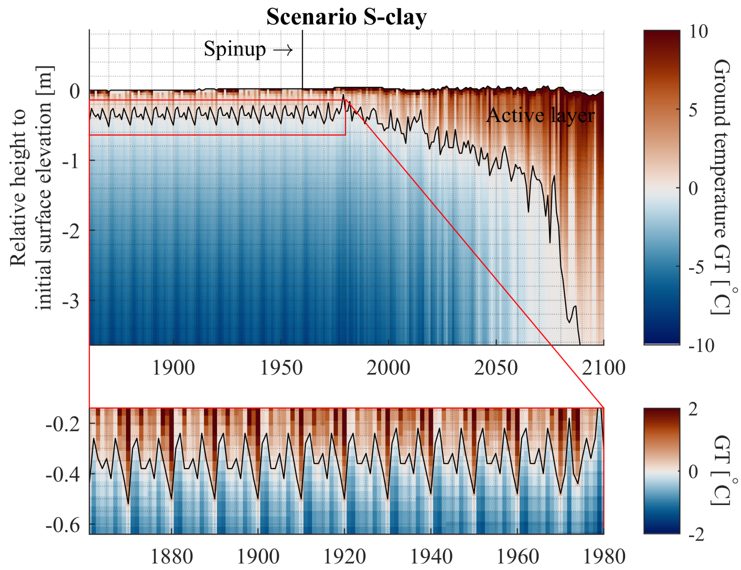
We follow the suggestion of the reviewer and used the relative height to the initial surface elevation in the figures 6, 9 and 11 (number 8, 11 and 13 in the revised version). An example is given below. Furthermore, changes in surface elevation have been added to the figures showing segregated ice (see comment above).



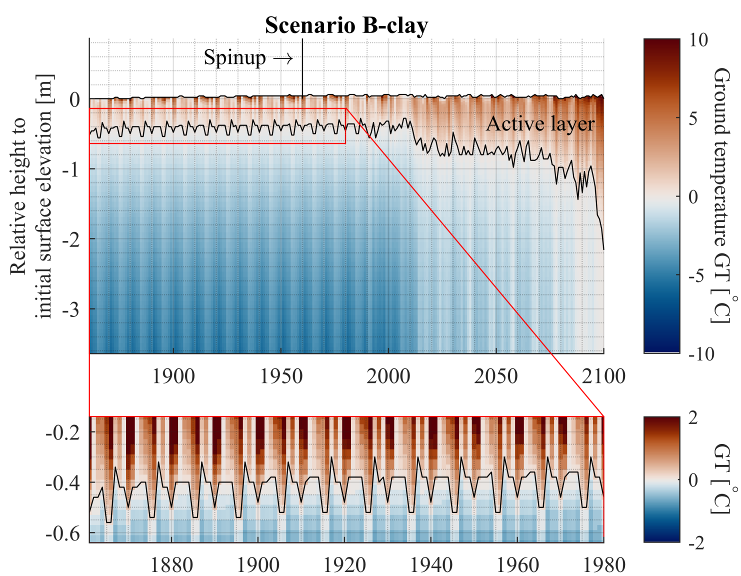
Sum of volumetric water and ice content in the permafrost on the reference date August 31 for the model run S-clay. *Dark blue colors indicate an increased volumetric water and ice content at the top of the permafrost, where ice segregation takes place. Values in the thawed layer are not displayed. The spin-up covers the years 1860 to 1960. The sum of volumetric water and ice content is shown as soil water can still occur below freezing temperatures dependent on the soil type. For scenario setup see Table 4.*

Furthermore, we changed the figures with the thermal gradients and saturation in the supplement, to clarify our argument. We present here the changes for the gradient in ground temperatures, but the figures for saturation were done in a similar matter.

Supplement, Line 28: *The forcing data set of Bayelva represents maritime climatic conditions compared to the continental setting in Samoylov and therefore less extreme temperature changes between summer and winter season. While the ground temperatures in the active layer are similar, the permafrost temperatures are much lower in model scenario S-clay compared to B-clay (Fig. S3 and Fig. S4). This leads to higher vertical gradients in ground temperatures at the top of the permafrost in Samoylov, enhancing the formation of segregated ice.*



Ground temperatures on the reference date August 31 for the model scenario S-clay. *The detailed plot shows the ground temperatures at the permafrost table during the spin-up, where ice segregation takes place.*



Ground temperatures on the reference date August 31 for the model scenario B-clay. *The detailed plot shows the ground temperatures at the permafrost table during the spin-up, where ice segregation takes place.*

Ll. 416-417: "In model scenario S-clay-rain50, the permafrost does not degrade to the end of the 21st century and no talik develops as less energy is consumed for thawing and melting of soil water under drier conditions" (underline by the reviewer). I am puzzled how this argument makes a sense.

This argument was not convincing and a mistake from our side. We have rewritten the part and reasoning should be clear now.

Line 503: *In model scenario S-clay-rain50, the permafrost does not degrade to the end of the 21st century and no talik develops. This can most likely be explained with a lower thermal conductivity of the soil under drier conditions (increasing from 1.04* $\mathrm{W\,m^{-1}K^{-1}}$ *(66 % saturation) to 1.67* $\mathrm{W\,m^{-1}K^{-1}}$ *(100 % saturation)), but other effects such melting of ground ice might play a role.*

L.419: "1908s" -> "1980s"?

Yes, this was a typo. It is corrected now.

Line 475: *When the same model set-up is run with forcing data from Bayelva (B-clay), which represents warmer permafrost under moist conditions, we obtain a comparable formation of segregated ice with a slightly lower maximum of 0.028 m in the 1980s compared to 0.034 m with forcing data from Samoylov (S-clay).*

Figure 7, ll. 418-425: A general feature of Figure 7 looks that the B-clay run produced more segregated ice compared to S-clay run after the 1980s except for the oscillatory decadal periods of comparable segregated ice formation in the 2020s, 2050s, and 2080s. It does not seem a simple warming phenomenon. The argument developed in this paragraph are not well-founded or convincing. Also, it is suspected that the vertical lines showing the end of the spinup periods may be off by 10 years or so if that for the S-runs ends in 1969 and that for the B-run ends in 1989.

It is true, that the model scenario *B-clay* produces more segregated ice compared to *S-clay* after 1980. This can be explained by the stabilization of the permafrost table over longer time periods (new segregated ice can form). In Samoylov, the active layer deepens faster, so that new segregated ice is melted directly in the following years. We rephrased the paragraph to clarify this for the reader.

The vertical lines showing the end of the spin-up period are correctly placed. While the spin-up for Samoylov repeats the years 1960-1969, the spin-up for Bayelva uses the years 1980-1989 (Table 3). The reason for this is, that we aimed to select a time period, that is most representative for earlier climate conditions at the field site (air temperatures, precipitation etc.). These are different for Samoylov and Bayelva.

Line 481: *During the time period 2020 to 2100, B-clay builds up more segregated ice in deeper soil layers. This can be explained by a slower increase of the active layer thickness compared to Samoylov Island, so that the permafrost table stabilizes for longer time periods, enabling new formation of segregated ice. As a consequence, less ground subsidence takes place for the Bayelva run.*

Figure 10. The scenario names are different from those found in Table 3 or text.

We corrected the scenario names in the figure caption.

Figure 12: *Column-accumulated segregated ice and surface elevation changes on the reference date August 31 for the model scenarios S-clay, S-clay-load5 and S-clay-load5-1980. A load that is acting on the soil column from the beginning of the simulation (S-clay-load5) suppresses ice segregation. A load that is added during thaw consolidation (S-clay-load5-1980) accelerates the process and the ground surface subsides faster.*

Ll. 478-480: I wondered the relative contribution of ice and sedimentation can be quantitatively assessed if the density of ice is constant (and it is apparently assumed so in this module).

The effective sedimentation rate is about 0.55 m per 1000 years. If the ground shows a subsidence of 0.286 m (*S-clay-sed1000*) between 1980 and 2100, it subsided effectively by 0.286 m in addition to approx. 0.066 m, corresponding to the deposited material during the 120 years.

Ll. 535-538: It is not clear which figures in supplement B would support the argument.

We added the figure number in the manuscript.

Line 593: *Moist conditions lead to more segregated ice compared to dry conditions, as more water is available for ice segregation (Fig. S1 in Suppl. S2) and the increased hydraulic conductivity supports the mobilization of soil water. Furthermore, high temperature gradients in the soil column (Fig. S3 in Suppl. S2) enhance ice segregation due to the temperature dependency of the soil matric potential in frozen state (Westermann et al. 2016).*

Ll. 554-555: "Due to the soil characteristics of the clay, mobile soil water occurs next to the ground ice and is pressed out due to higher total stress" It is not clear whether this statement is meant to be general explanation of the real world, or the result description of the model. Similar ambiguity or confusion was found sporadically in the text.

Thanks for pointing out this issue. We changed the wording in the manuscript.

Line 614: *Due to the selected soil characteristics of the clay in our model setup (Table 3), mobile soil water occurs next to the ground ice and is pressed out due to higher total stress.*

Ll. 565-566: “Therefore, the time period available for the formation governs today’s segregated ice content.” This is another example of the above issue.

We rephrased the sentence.

Line 626: *The shift of the freezing front leads to a thickening of the ice-rich soil layers as demonstrated in this study (Sect. 3.6). Our results show that longer periods of sedimentation result in thicker ice layers, with the sedimentation rate influencing the overall ice content of the accumulated layers.*

L. 621: It is not clear what “fields sites affected by carbon-rich soils” mean or denote.

We clarified this statement and changed it in the manuscript.

Line 740: *As these soils are sensitive to changing stress conditions due to a high compression index, it could be beneficial to apply the new model scheme for field sites with high carbon contents in the soil stratigraphy.*

L. 642: It is not clearly stated which part of the manuscript support the claim of being able to “lead to improved simulations of ice-rich ground responding to a warming climate.”

We added a statement in the manuscript.

Line 763: *In this study, we present a new model scheme for the CryoGrid community model, which demonstrates ice segregation as well as thaw consolidation. The model is capable of building up layers of segregated ice with associated ground heave and calculating subsidence upon thawing, which can improve simulations of ice-rich ground responding to a warming climate.*

Ll. 650-652: “Climatic conditions, which lead to large gradients…” It is not general “climatic conditions” but warm and moist conditions that derive. It needs to be specific and precise. It is suggested to check the overall manuscript from this perspective.

This is a valid point. We clarified it in this paragraph as well as in other parts of the manuscript.

Line 772: *The model results suggest that several factors play an important role in the formation and melt of segregated ice such as (i) ground temperature gradients and soil water content, (ii) soil type and (iii) external loads. (i) Large gradients in ground temperatures, as well as high soil water contents in the active layer through high precipitation support ice segregation.*

Line 374: *All other scenarios are based on a simplified stratigraphy and are designed to analyze different influencing factors: (i) soil water contents and ground temperatures, (ii) soil type (sand, silt, clay and peat), (iii) external loads and (iv) sedimentation.*

We changed the title of section 3.3 to *Sensitivity towards soil water content and ground temperatures*

Line 463: *Model simulations with different forcing data sets suggest that ice segregation is highly dependent on the climatic conditions, which can lead to different soil water contents and ground temperatures.*

Line 590: *We identify several factors, which influence the soil mechanical processes: (i) soil water contents and ground temperature gradients, (ii) soil type and (iii) external ground loading, which will be discussed in the following.*