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Simulating ice segregation and thaw consolidation in permafrost environments with the CryoGrid community model

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S1: Description of applied CryoGrid stratigraphy classes

Ground stratigraphy classes provide user-defined information about the ground material, which consists of mineral, organic, ice, water and air fractions. If seasonal snow cover should be accounted for, the ground stratigraphy class is coupled to a snow class by using a twin called "CLASSNAME_snow". A detailed description of stratigraphy classes in the CryoGrid community model can be found in Westermann et al. (2023).

GROUND_freezeC_RichardsEq_seb_pressure: This is the new stratigraphy class presented in this study. It is based on the former stratigraphy class *GROUND_freezeC_RichardsEq_seb* as described in Westermann et al. (2023). The stratigraphy class is applied to the upper 9 m of the soil column in all model scenarios. It computes the surface energy balance as an upper boundary condition, the freezing characteristics of Painter and Karra (2014), a water balance based on Richards equation and soil mechanical processes.

GROUND_freezeC_RichardsEqW_seb_pressure_sedimentation: This stratigraphy class includes all functionalities of the stratigraphy class *GROUND_freezeC_RichardsEq_seb_pressure* in addition to user-defined sedimentation.

GROUND_freeW_seb: This is a stratigraphy class presented in Westermann et al. (2023), which is used below 9 m depth in all model scenarios. It includes the surface energy balance, free water freezing characteristics and a bucket scheme water balance.

SNOW_crocus2_bucketW_seb: This is a snow class presented in Westermann et al. (2023), which is applied in all model scenarios. It takes into account the surface energy balance, snow microphysics as well as a bucket scheme snow hydrology. Melt water is pooled up to the snow surface.

S2: Saturation and ground temperatures of the soil column in model scenarios *S-clay*, *S-clay-rain50* and *B-clay*

The following figures show the saturation of the ground column (model scenarios *S-clay* and *S-clay-rain50*) as well as ground temperatures (model scenarios *S-clay* and *B-clay*). The soil water and ground temperature conditions are used for the discussion of the dependency on climatic conditions (chapter 3.3).

While the soil column is predominantly saturated below the permafrost table, the active layer experiences changes in soil water content due to precipitation and evapotranspration. As less rainfall is available in *S-clay-rain50* compared to *S-clay*, the soil water content in the active layer is reduced. With a deepening of the active layer, the soil water content can be decreased also in larger depths, increasing the effective stress and thus causing soil compaction. Temporarily increased soil water contents during future forcing (e.g. 2070 to 2080 in *S-clay*) can result in soil swelling due to the buoyancy effect.

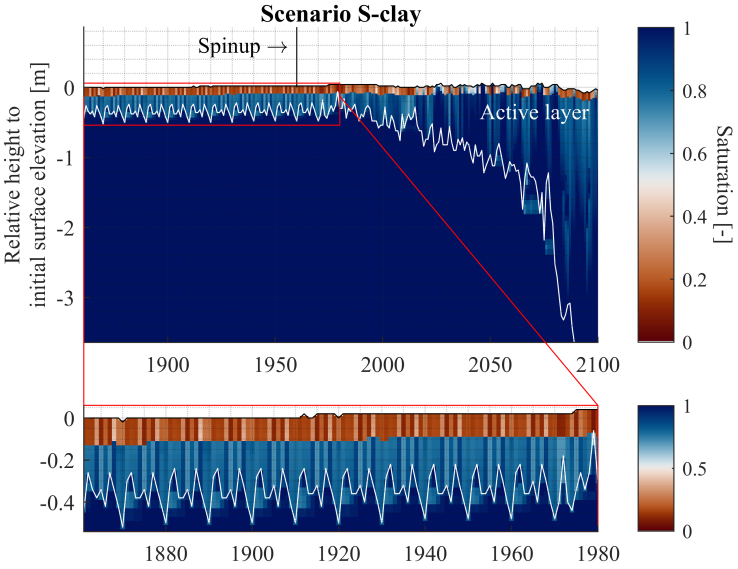

Figure S1. Saturation on the reference date August 31 for the model scenario *S-clay*. The detailed plot shows the saturation in the active layer during the spin-up. For scenario setup see Table 4.

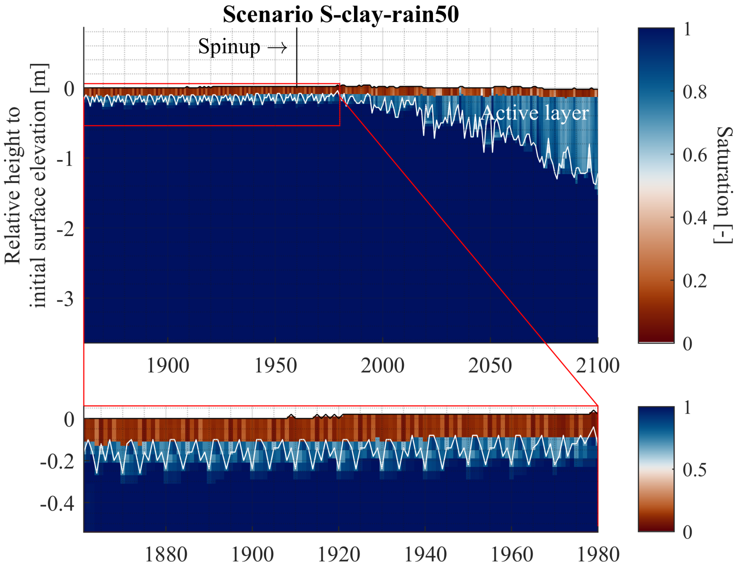

Figure S2. Saturation on the reference date August 31 for the model scenario *S-clay-rain50*. The detailed plot shows the saturation in the active layer during the spin-up. For scenario setup see Table 4.

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.

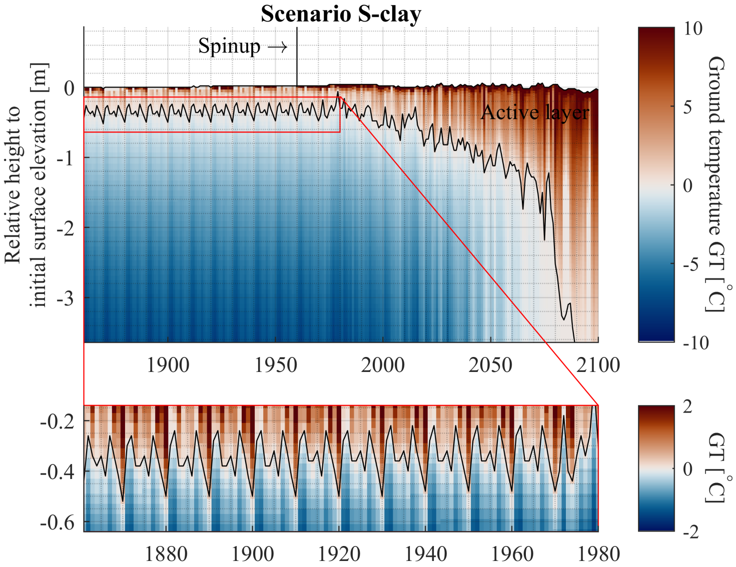

Figure S3. Ground temperatures on the reference date August 31 for the model scenario *S-clay*. The detailed plot shows the ground temperatures at the permafrost table during the spin-up, where ice segregation takes place. For scenario setup see Table 4.

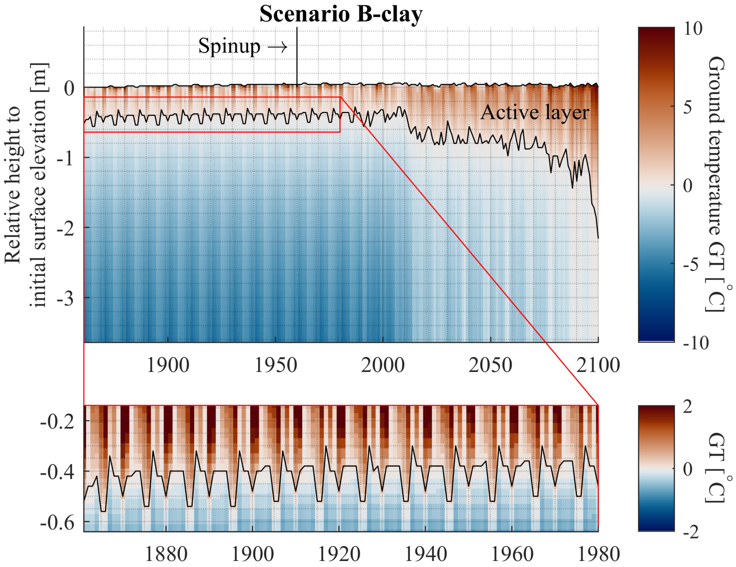

Figure S4. Ground temperatures on the reference date August 31 for the model scenario *B-clay*. The detailed plot shows the ground temperatures at the permafrost table during the spin-up, where ice segregation takes place. For scenario setup see Table 4.

S3: Volumetric water and ice contents of the sedimentation runs *S-clay-sed350-3x* and *B-clay-sed370-2x* for comparison with in situ observations

We perform two model scenarios with increased sedimentation rates for Samoylov Island (*S-clay-sed350-3x*) and the Bayelva field site (*B-clay-sed370-2x*). The effective sedimentation rates are 1.7 $\mathrm{mm\,a^{-1}}$ (Samoylov) and 1.1 $\mathrm{mm\,a^{-1}}$ (Bayelva). Both scenarios show formation of segregated ice at the top of the permafrost and a thickening of the ice-enriched layer with progressing sedimentation. With ongoing climate change, the ground subsides until 2100, even though the sedimentation continues due to the melting of ground ice. The following figures show the volumetric water and ice contents, including the volumetric segregated ice contents in the ice-enriched layer at the top of the permafrost. In the 1980s, the volumetric water and ice content is 60.4 % (68.8 %) and the volumetric segregated ice content is 5.4 % (13.6 %) for Samoylov (Bayelva). These values are compared to in situ observations in Sect. 4.4.

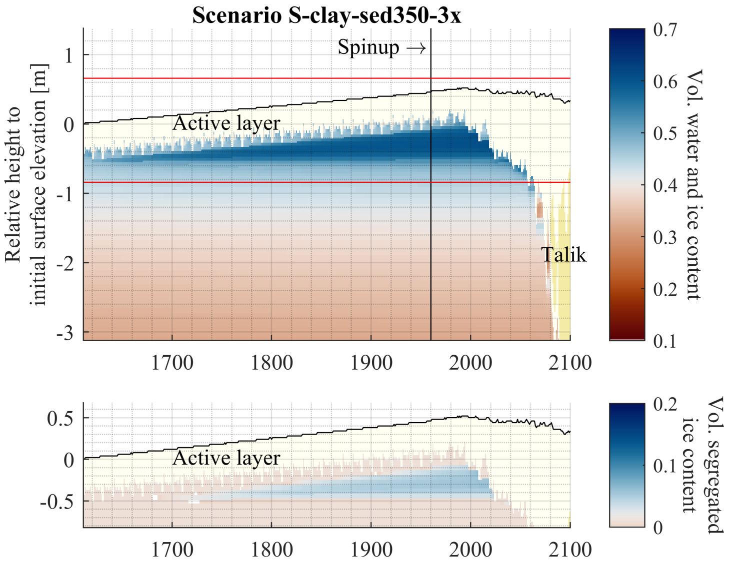

Figure S5. Volumetric water and ice content and volumetric segregated ice content on the reference date August 31 for the model run *S-clay-sed350-3x*. Dark blue colors indicate an increased volumetric water and ice content at the top of the permafrost, where ice segregation takes place. Values in the thawed layer are not displayed. The 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.

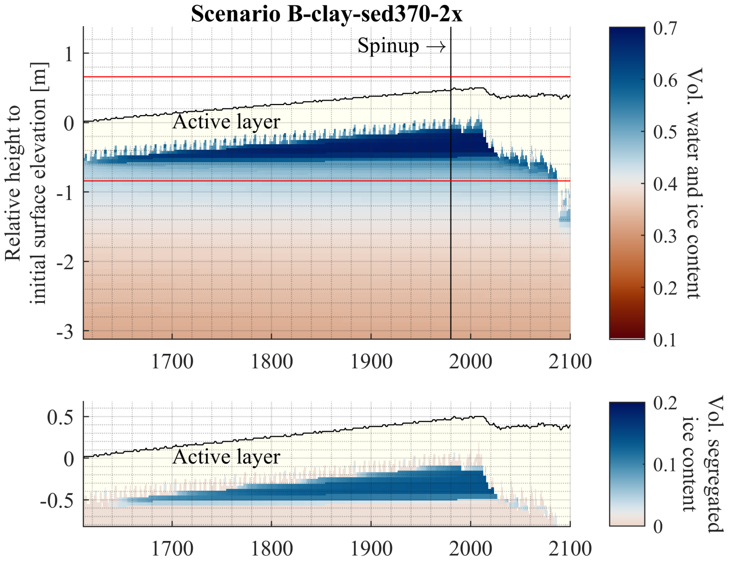

Figure S6. Volumetric water and ice content and volumetric segregated ice content on the reference date August 31 for the model run *B-clay-sed370-2x*. Dark blue colors indicate an increased volumetric water and ice content at the top of the permafrost, where ice segregation takes place. Values in the thawed layer are not displayed. The 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.

S4: Control runs without formation of segregated ice

We perform a model run based on the peat stratigraphy (Table 3) without ice segregation (*S-peat-control*). To do so, we suppress water flow into already saturated and frozen grid cells, while the rest of the functionality of the model stays the same.

The model scenario *S-peat* forms segregated ice predominantly between 1861 and 2000 (Sect. 3.4). During this time period, the active layer thickness is on average 0.054 ± 0.029 m shallower for *S-peat* compared to *S-peat-control*. As *S-peat* forms segregated ice at the top of the permafrost each year, this excess ice melts partly in the following year, consuming energy, which is consequently not available for warming of the ground. As *S-peat-control* does not contain segregated ice, the energy can be used directly to warm the ground, resulting in a deeper active layer.

In the time period 2000 to 2010, large parts of the segregated ice are melted in *S-peat* (Sect. 3.4). Again, this process requires energy, even more than during 1861 to 2000, as more ground ice is melted during these years. Therefore, the difference in active layer thickness increases to 0.078 ± 0.088 m on average, with *S-peat* having the shallower active layer than *S-peat-control*.

From 2010 to 2100, *S-peat* forms less segregated ice, however, ice segregation continues at the top of the permafrost on a smaller scale (Sect. 3.4). Therefore, a shallower active layer is still simulated for *S-peat* compared to *S-peat-control*, even though the difference in active layer thickness decreases to 0.039 ± 0.053 m on average.

The comparison between *S-peat-control* and the model scenario *S-peat* with ice segregation shows, that the formation of segregated ice leads to shallower active layers, especially during the periods where the ice-enriched soil layer thaws. This can be explained by the energy required for ground ice melt, which is then not available for ground warming.

References

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