Response to referee Sebastian Uhlemann

We would like to thank Sebastian Uhlemann 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 (added text) and red (deleted text). Line numbers are referring to the revised manuscript.

General Response

This paper introduces a physically-based slope stability index, integrated within the geomechanical module of the CryoGrid community model, to evaluate climate-induced slope instability in ice-rich permafrost environments.

The implementation of this geomechanical scheme represents a significant step forward in modeling and understanding the impacts of climate change on permafrost slope failures. By moving beyond empirical or statistical approaches, the integration of these geotechnical formulations into a model that dynamically simulates permafrost thermal and hydrological regimes provides a valuable tool for assessing landscape-scale vulnerabilities. A particular strength of this work is the development of the Thawing Slope Stability Index (TSSI) and its application to bridge process-based modeling with regional-scale observations on Banks Island, Canada.

However, while the model successfully captures broad susceptibility trends, there are still several limitations and mechanistic gaps that the manuscript should highlight more thoroughly. Specifically, the manuscript would benefit from a more explicit discussion regarding the physical limitations of the model setup such as the treatment of subsurface lateral fluxes, bulk density changes during thaw, and the influence of variable snow distribution. Some of those points are discussed in the Limitations section, but they should be discussed upfront, not as an afterthought. Furthermore, clarifying the distinction between the simulated active layer detachment failures (ALDF) and the retrogressive thaw slumps (RTS) used for validation early in the text will better contextualize the model's capabilities and its current constraints.

Overall, the paper is well-written, timely, and makes an important contribution to the field of permafrost geohazards. Please see some more detailed comments below for further refinement.

We thank Sebastian Uhlemann for his detailed feedback, which helped to improve the manuscript. We address all points raised in the general response in the detailed comments below.

Detailed Comments

1. Conceptual and Terminology Clarifications

The methodology section should explicitly highlight that the developed model accounts for the failure process of ALDFs. Because ALDFs frequently initiate RTSs, validating the model against an RTS database is perfectly valid, but this specific limitation and linkage should be clearly established early on.

We clarified throughout the entire manuscript (abstract, introduction, methods, discussion, conclusions) that the model represents the failure processes of ALDF, and explained the reasoning for using the RTS database for validation. To do so, we added a new section in the methods (2.5 Model validation).

Line 7 ff.: *The model was tested using a multi-decadal database of RTS initiation for an area of 2300* km^2 *on Banks Island, Canada. We used RTS as a proxy for ALDF, since the majority of RTS in the field area were triggered in warm summers by exposure of massive ice following ALDF.*

Line 69 ff.: *In this study, we calculate the factor of safety within the framework of a land surface model and evaluate the potential for slope failure by introducing the Thawing Slope Stability Index (TSSI). This approach represents a physically-based, climate-dependent assessment of the susceptibility to ~~slope failure~~ ALDF in ice-rich permafrost.*

Line 148 ff.: *The existing model functionalities are extended to represent the processes associated with slope failures in ice-rich permafrost, specifically active layer detachment failures (ALDF).*

Line 261 ff.: **2.5 Model validation**

The model represents the processes resulting in active layer detachment failures (ALDF), however, no inventory of ALDF was available to support a statistical analysis of their occurrence. Therefore, we used a long-term inventory of newly initiated retrogressive thaw slumps (RTS) for validation (Lewkowicz and Way, 2019). The observed peaks in RTS initiation were associated with exceptionally warm summers and a deepening of the active layer. Lewkowicz and Way (2019) point out that the main trigger of RTS in the field area was ALDF exposing massive ground ice, while fluvial, lacustrine and coastal erosion may have acted as pre-conditioners to RTS initiation but cannot explain the high numbers of newly initiated RTS within the same year. Consequently, the RTS database can be used as a proxy for ALDF.

Line 323 ff.: *The modelling produced a range of values across the study area with positive median TSSI of 5.2-18.4 for 1998, 2010, 2011, and 2012 (Table 3 and Fig. 6a), indicating a high likelihood of ALDF~~and RTS initiation~~.*

Line 385 ff.: *This study advances the field in four main ways. First, it demonstrates that the geomechanical model that was incorporated in the CryoGrid community model by Aga et al. (2023) can be used within an infinite slope analysis to predict potential slope instability, which may lead to the initiation of ALDF ~~or RTS~~ and potentially RTS when triggered by exposure of massive ice through ALDF.*

Line 403 ff.: *Third, the validity of the TSSI as an indicator of slope instability was demonstrated by comparing it to a long-term inventory of newly observed RTS (Lewkowicz and Way, 2019). The ~~majority is linked to warm summer, so that their initiation is likely connected to~~ occurrence of new RTS peaked in warm summers, since the main trigger of RTS in this field area were thaw-driven ~~slope instabilities such as ALDF , rather than slope-undercuttings or blockfalls, so that the database was well suited for evaluating the model results.~~ALDF exposing massive ice (Lewkowicz and Way, 2019). The database is therefore a suitable proxy for ALDF occurrence (Sect. 2.5).*

Line 479 ff.: *As a result of the limitations and uncertainties, the model captures the susceptibility to slope failure in ice-rich permafrost, specifically ALDF, at a landscape scale but it does not predict the locations of individual events.*

Line 493 ff.: *The presented model could be a valuable tool for further investigations of the triggers for ALDF ~~, in addition to RTS, in~~ in ice-rich permafrost environments.*

Line 507 ff.: *In this paper we describe the incorporation of a physically-based infinite slope analysis within the CryoGrid community model to develop a multi-decadal time series of the factor of safety for ice-rich permafrost slopes, representing the processes leading to active layer detachment failures (ALDF).*

Line 517 ff.: *The TSSI was tested in a study area on Banks Island where hundreds of newly initiated retrogressive thaw slumps (RTS) occurred between 1985 and 2015. ~~These~~ In this study, we use RTS initiation as a proxy for ALDF, as the exposure of massive ground ice through ALDF was reported as the main trigger for RTS initiation (Lewkowicz and Way, 2019). The newly initiated RTS developed in years with positive TSSI and were concentrated spatially in areas of the landscape with the highest TSSI values.*

The TSSI should not be explicitly termed a "likelihood," as its mathematical definition represents a cumulative duration and magnitude of risk rather than a strict statistical probability.

That is true. We changed the wording in the revised version of the manuscript.

Line 177 ff.: *The TSSI, therefore, indicates the ~~likelihood of~~ cumulative duration and magnitude of risk for slope failure based on the physical processes of thaw active in the ground.*

2. Missing Physical Mechanisms

The manuscript asserts that elevated pore pressures are a primary triggering condition, yet the simulations do not show an obvious correlation between unstable conditions and precipitation. In many field settings, elevated landslide occurrence is closely tied to wet summers; this discrepancy and the limited direct effect of summer rainfall on the simulated slope stability require further explanation. This suggests there is still missing understanding on why and when these slopes fail.

The model results show that high pore water pressures can build up at the top of the permafrost, even when the lower part of the active layer is not fully saturated. The coexistence of ground ice and liquid water reduces the hydraulic conductivity, resulting in a slow drainage of the melt water and leading to unstable conditions. We added this in the results and discussion.

Line 308 ff.: *Unstable conditions were mainly simulated to occur in the uppermost excess ice layer, in which ground temperatures were just below* 0°C *and where ground ice coexisted with liquid soil water (Table 3). ~~The presence of an ice phase restricted the pathways for the melt water~~ An example is illustrated in Fig. 4, showing that the unstable conditions occur at the top of the permafrost. In this zone, the presence of ice caused a drastic reduction in hydraulic conductivity: while the lowest unfrozen grid cell in the active layer had simulated hydraulic conductivities of 1.5×10-8 to ~~drain~~ 3.2×10-8* ms^{-1}*, the unstable grid cells with coexisting ground ice and liquid water exhibited much lower values of 5.6×10-12 to 8.5×10-11* ms^{-1}*. This strong reduction in hydraulic conductivity restricted the drainage of meltwater into the unfrozen active layer~~resulting in~~, even when the active layer itself was not fully saturated, thereby promoting excess pore water pressures.*

Line 413 ff.: *The example presented from Banks Island shows that years with high summer air temperature and high incoming short-wave radiation in summer resulted in unstable conditions and the formation of RTS~~. This~~, while precipitation and thus the degree of saturation in the active layer played a minor role at this field area. The model results show that unstable conditions can be traced back to high pore water pressures, which build up when the drainage of liquid water is restricted by clogging of the pathways by coexisting ground ice. These findings are in line with Dai et al. (2025), who showed that temperature-driven RTS dominate over precipitation-driven RTS in high latitudes. However, the model could also be applied at field areas, where precipitation dominates the susceptibility to slope failure.*

While the model details how the internal friction angle and cohesion adapt to ice content and temperature, it is unclear if the model accounts for the change in normal stress. The phase change from ice to water inherently increases the bulk density of the material, which should alter the normal stress. You refer to this in the discussion of the limitations,

but there it is rather brief, and I think this should be discussed in the model setup to be upfront with potential limitations.

We clarified this in the methods.

Line 101 ff.: *The CryoGrid geomechanical scheme computes the stress conditions in the soil, with the total normal stress being the sum of the vertical geostatic stress and external loads. The normal stress varies over time with changes in the weight of the overlying soil. As the mineral and organic content stays constant throughout the simulation, variations are controlled by the water balance, namely infiltration and evaporation, while variations in density due to phase changes of the water were not considered to ensure compatibility with other CryoGrid modules. The effective stress acting on the soil matrix is subsequently obtained by subtracting the pore water pressure from the ~~total~~ normal stress...*

The discussion of "convective fluxes" needs clarification on whether it refers strictly to density-driven fluxes or if it includes advective fluxes. On hillslopes, a relatively thin advective layer can result in significant lateral downslope flow. Furthermore, if the model incorporates lateral fluid flow, it should be clarified whether this simultaneously drives lateral heat flow. You also mention this in the limitations section, but again, I think that this should be highlighted earlier on, and then the impacts of not considering advective flow should be discussed in the discussion section.

We clarified these points in the manuscript. We added in the methods how lateral water fluxes in the subsurface are implemented in the model, and added an explanation why it was not feasible to account for them with our clustering approach. We also mention in the discussion that lateral water fluxes can lead to seepage forces, which can increase the instability of the slope.

Line 97 ff.: *The CryoGrid community model computes both conductive and convective heat fluxes within the ground. The former is based on Fourier's law, where the dominant factor is the thermal conductivity of the ground. The latter is governed by water fluxes in the soil, driven through gravity in the saturated domain and gradients of the matric and gravitational potential in unsaturated conditions.*

Line 132 ff.: *~~We included~~ The CryoGrid community model can represent lateral water fluxes ~~(Westermann et al., 2023) in addition to vertical water movement~~ by coupling to an external water reservoir (Westermann et al., 2023) or laterally coupled tiles, which can exchange both water and heat fluxes (Nitzbon et al., 2019, 2020; Martin et al., 2021). Applying lateral water fluxes in this study ~~. Surface runoff was based on the~~ would have required information on the thermal state and water balance of all neighboring tiles throughout the entire simulation, implying that a separate model realization would have been necessary for each 10 x 10 m^2 grid cell. For computational efficiency, we clustered the field area, reducing the model realizations to 20 (Sect. 2.3) at the cost of neglecting lateral water fluxes in the subsurface. Lateral water fluxes on the surface, however, were still represented using the Gauckler-Manning equation (Gauckler, 1867; Manning et al., 1890), which depends on the slope* *angle and the Gauckler-Manning roughness coefficient. The surface runoff was removed from the system.*

Line 462 ff.: *Due to the clustering approach, a one-dimensional ~~model setup ,~~ setup was necessary, so that lateral water fluxes in the subsurface were neglected and the same drainage conditions were applied to all grid cells. ~~Theoretically, such~~ This increases the uncertainty in the model results, as lateral water fluxes can cause seepage forces that significantly reduce slope stability (Vargas Ceron et al., 2025). Theoretically, lateral fluxes could be implemented within the framework of the CryoGrid community model based on the topography, by including external water reservoirs (Westermann et al., 2023) or laterally coupled tiles (Nitzbon et al., 2019, 2020; Martin et al., 2021). However, both runoff and subsurface water flow are three-dimensional, and complex flow patterns can arise through preferential water tracks (Evans et al., 2020) or the microtopography of the frost table (Chiasson-Poirier et al., 2020). Consequently, it is a challenge to correctly set the drainage conditions over large spatial scales.*

3. Spatial and Topographic Controls

The model implementation should address whether the natural variability of snow distribution is reflected. Thicker snow accumulation in topographic depressions versus thinner snow on uplands creates thermal conditions that could increase ground temperatures at the toe of a slope, potentially reducing shear strength and increasing failure risk. Whether or not this is reflected in the model remained unclear to me.

The model can in theory account for the natural variability of the snow distribution by applying different snowfall factors. In our study, we set a constant snowfall factor for simplicity, as the snowpack is typically thin on Banks Island. We clarified this in the revised manuscript.

Line 140 ff.: *To simulate the seasonal snow cover, the CryoGrid community model inherits the functionalities of the Crocus snow model (Vionnet et al., 2012) as described in Zweigel et al. (2021) and Westermann et al. (2023). It takes into account snow microphysics, the surface energy balance and snow hydrology. Upon melting, excess water accumulates and is transferred as standing water to the uppermost grid cell of the local stratigraphy class. From there, it either infiltrates or is discharged as surface runoff if soil properties and moisture conditions prevent infiltration. It should be noted, however, that as implemented in this study, surface runoff does not affect adjacent cells. The snowfall can be scaled through a snowfall factor, reducing or increasing the snowfall from the atmospheric data.*

Line 252 ff.: *To assess the performance of the ground thermal modelling for the study area, we ran the model for a site in Aulavik National Park, where ground temperature data from a borehole was available from 2010 to 2018 (Permafrost Laboratory/ University of Fairbanks, 2025), based on ERA5 data for this location. A snowfall factor of 0.5 was necessary to achieve a good fit with observed winter temperatures (Appendix A). The same snowfall factor was then applied to the study area in* *southeastern Banks Island where no observations were available. This relatively low snowfall factor can be explained by snow sublimation and significant wind redistribution which results in snow accumulations in topographic hollows, while the uplands typically exhibit little to no snow cover (Sect. 2.2; French, 2017). The model would also allow to cluster the field area by snowfall factor, in addition to slope angle and aspect, for example based on satellite imagery. However, we applied a constant snowfall factor for simplicity, as the snowpack is typically thin on Banks Island due to sublimation and wind redistribution (French, 2017).*

Line 452: *In the model ~~testing~~setting, we assigned constant soil properties across the study area. However, spatial variations in ground ice content and sediment characteristics exist, as shown by O'Neill et al. (2022) in relation to ground ice content and are linked to the glacial origin of the sediments (Lakeman and England, 2012). Furthermore, natural variabilities in the snow distribution likely occur due to topographical features (French, 2017). Despite the promising results achieved that reconstructed the occurrence of newly observed RTS in the area, there were local discrepancies between model results and observations. Clustering the area with land cover types~~and~~ , ground ice contents and different snowfall factors in addition to slope angle and aspect, could improve the model predictions. ~~This~~ These option exists within the CryoGrid community model and ~~its~~ their implementation is simply limited by available data. This could allow the assessment of the susceptibility to slope failure over large spatial scales, with varying subsurface properties. The depth of the excess ice layer is particularly critical as it determines whether the thaw plane reaches the excess ice during extreme summers, and thus controls the occurrence of unstable conditions.*

Because the results are described based on topographical clusters, it would be highly beneficial to include a figure showing the simulated responses (either permafrost conditions or slope stability) separated by these specific clusters. This would clearly illustrate which "types" of slopes are most vulnerable and which remain stable.

We added a subfigure (Fig. 7a) that shows the TSSI for each cluster in 1998. This figure also indicates which combination of slope angle and aspect correspond to the 20 clusters. We also revised the text accordingly.

Line 358 ff.: *The relationship between TSSI and aspect is weak (Fig. 7~~b~~a & c). High susceptibility occurs across all cardinal directions, and TSSI varies substantially even among similar aspects (e.g., east-facing slopes). This variability is ~~mainly due to slope angle~~ primarily controlled by slope angle (through the occurrence of steep in all cardinal directions), which exerts a stronger influence than aspect and thus masks ~~aspect effects. Restricting the~~ any aspect-related signal. The weak dependency on aspect is also evident in the observed RTS: 25% are north-facing, 41% east-facing, 18% south-facing and 16% west-facing (each defined as the cardinal direction ± 45°). This distribution reflects well the peaks in TSSI shown in Fig. 7c. To reduce the masking effect of steep slope angles, Fig. 7d restricts the analysis to gentle slopes (<~~5°)reveals a slight increase in TSSI for south-east facing slopes~~ 4°), which reveals that the highest values for TSSI are found for east- and south-facing slopes,* *aligning with the expected impact of increased solar irradiation*.

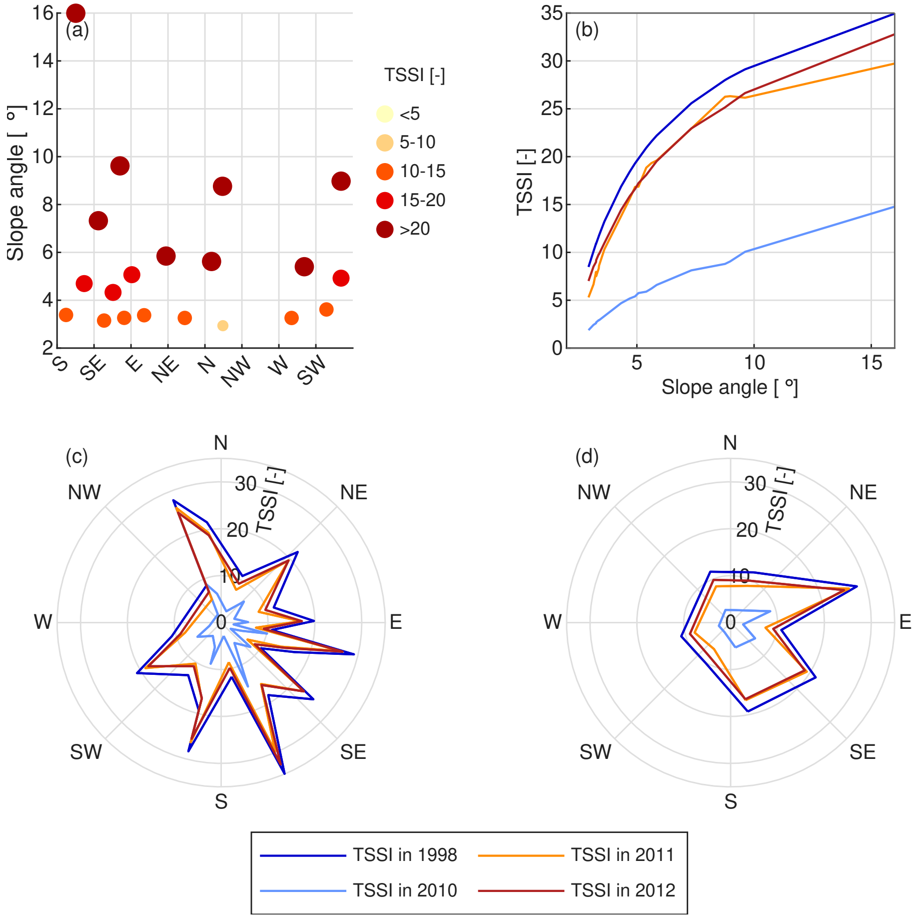

Figure 7. Relationship between the simulated TSSI ~~for years with median positive values~~ and (a) slope angle and aspect in the year 1998, (b) slope angle, (c) aspect ~~. Soil properties were assumed to be the same in all~~ and (d) aspect for clusters with slope angles <= 4°. Note: Years with a mean TSSI of zero are not shown.

While the results suggest that high susceptibility occurs across all cardinal directions, there appears to be a higher prevalence for easterly to southerly facing slopes. This nuance should be addressed, as it aligns with the expected impact of increased solar irradiation.

We extended the results section and the discussion on the aspect-related signal based on the comments of reviewer 1. We also included that the slightly higher susceptibility for east- and south-facing slopes align with the expected impact of increased solar radiation. For changes in the results section, see the comment above. Changes in the discussion section are given below.

Line 395 ff.: *Representing the topography by clustering proved essential because ~~both~~ slope angle and to a limited extent also aspect influence the TSSI. The slope angle appears in the equations to calculate the factor of safety and thus determines the TSSI. Aspect affects the TSSI indirectly by controlling the ground temperatures and active layer thickness, especially through differences in incoming short-wave radiation. ~~Although both parameters varied only slightly among the clusters, these minor differences led to notable variations in TSSI, underscoring their importance even for~~ The weak dependence on aspect indicates that variability in thaw-driven slope instability on Banks Island is only little influenced by differences in short-wave radiation, consistent with the similar weak signal in the observational data. In landscapes with steeper terrain and stronger topographic shading, however, the influence of aspect is likely to be more pronounced. But also the relatively small effect in the gently undulating terrain of Banks Island underscores the importance of slope angle and aspect when assessing susceptibility to slope failure.*

You have developed an impressive tool that truly advances the state of the art in permafrost modeling. I hope this feedback is helpful as you finalize this excellent paper.