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Interactive comment on "Consequences of permafrost degradation for Arctic infrastructure – bridging the model gap between regional and engineering scales" *by* Thomas Schneider von Deimling et al.

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We thank the reviewers for their constructive comments which are very helpful for improving our manuscript. Based on the comments made by both reviewers, we have especially reworked our perspective section. We also extended our model simulations to explore long-term model behaviour beyond the year 2100 and investigated further model diagnostics to explore in more detail the model physics discussed, especially with respect to talik formation. In the following we reply in detail to all the comments made:

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Reviewer 1: ...However, two general concerns I have are that: 1) I would like the authors to elaborate more on the outline they propose in section 4 for how to expand simulations like those reported here to a pan-Arctic risk assessment, and 2) I would appreciate a bit more discussion of the permafrost physics in the simulations from their Dalton Highway case study. In addition, I have several more specific comments, listed below.

General comments: 1) I appreciate that the authors sketch out how to incorporate PTMs into pan-Arctic risk assessments in section 4, but currently the proposed workflow is somewhat difficult to understand. I know that this section is speculative, but I'd like a bit more detail about the connection between LSMs and PTMs. The authors state that results from an initial set of PTMs "could ... be used by LSMs to define a tiling-based model-setup for describing infrastructure in a reduced but manageable manner." Dtalikoes this mean that a pan-Arctic LSM simulation would be executed, incorporating a sub-grid tiling scheme that accounts for the location of infrastructure? And if so, how would this be more informative than simply using meteorological forcing data derived from ESMs in the initial set of PTMs?

We have intensively reworked section 4 to substantiate our suggested strategy for connecting PTMs with LSMs and GTMs (see below, end of general comments reply) where we now stress more clearly the difference in applicability and informative values between LSM and GTM analyses. We now sketch out three main lines of connecting PTMs and LSMs/ESMs

1) PTMs can support LSM development for defining suitable tiling-based descriptions of infrastructure such that LSMs can be used for calculating large-scale estimates of potential risks regarding infrastructure failure. LSMs would not account for the exact location of infrastructure, but rather for the general presence of infrastructure within a LSM grid cell. Infrastructure in each grid cell is then subject to the climatic conditions taken from the corresponding atmospheric fields of each LSM grid cell (rather than to site-specific local climate). 2) PTMs could be used as an offline add-on in LSMs for

capturing infrastructure. 3) PTMs could be run in stand-alone mode driven by climate conditions from an ESM (like done in this study). This allows the accounting of more site-specific aspects (e.g. local soil stratigraphy, bias-corrected climate forcing, etc.) For details see new section 4 below.

2) I am also curious at what stage of the analysis it is most appropriate to assess uncertainty related to the site-specific manners in which infrastructure may accelerate permafrost thaw. The authors acknowledge that “a specific gravel road can deviate strongly from our assumed setting here.” As they state, one source of variability is road geometry, and another source of variability is that gravel roads can cause thaw through a variety of mechanisms, such as low-albedo dust deposition on the tundra or impedance to surface drainage. Another important factor to consider is that, unlike the case study presented here, the effects of these process are often asymmetrical, occurring preferentially on one side of the roadway (e.g., Raynolds et al., 2014; Abolt et al., 2017). It seems like uncertainty in each of these factors would have a big impact on the risk assessment. Is it best to account for it within PTMs, LSMs, or GTMs?

We agree that these factors are all critical for judging infrastructure failure at a given location. For such cases, the capturing of these processes likely requires the use of complex fully coupled thermal-hydrological 3D modelling. If the focus is more on a regional or pan-arctic risk assessment, site-specific factors are of less importance but it will be crucial to describe controlling factors (such as ponding next to a road) which determine overall infrastructure failure on a regional scale. The potential risk will not depend on where exactly infrastructure will fail, but on the occurrence of infrastructure failure under climatic conditions typical for a given grid cell. Such analyses could be performed with PTM-LSM setups.

In the revised section 4 we also sketch out in more detail how PTMs can support GTM analyses for determining infrastructure failure under climate change.

3) The authors state in the abstract that rates of permafrost thaw adjacent to the high-

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way follow “a two-phase behavior”, and in section 3.2, they state that thaw rates sharply increase “once a critical warming of the ground has been reached.” This is an important result and I think it would be worthwhile for the authors to elaborate more on when this threshold occurs. For example, does the abrupt increase in thaw coincide with events such as the formation of an open talik, or the onset of surface water pondingâĔŸA ĔĞTor does it lag several years behind? Also, does the system stabilize by the end of the simulations? This information would be informative to the risk assessment, and I also think it would be interesting in the context of other numerical simulations of thermokarst.

We consider these aspects interesting diagnostics for the model result interpretation and have analyzed talik formation dynamics and performed a climate stabilization scenario to investigate long-term thaw dynamics. Our analyses show that the timing of increase in thawing rates can occur well before full talik formation. Yet the choice of a less strong criterion for soil refreeze allows us to broadly track the two phase behaviour. We achieve this by determining the timing of the formation of a partially unfrozen soil layer, where refreeze does not exceed 25% of pore water (see the timing indicated by dashed vertical lines in the updated Figure 5 below). In the manuscript we now discuss this aspect as follows: “... Thawing rates can be split into two periods: a period of slow and gradual increase in maximum thaw depths, followed by a sharp increase in thawing rates once a critical warming of the ground has been reached. The two-phase thawing characteristic cannot be explained through changes in external climate forcing (see Figure A3), but by internal dynamics following the formation of year-round partially unfrozen layers in the ground. We can roughly track the timing of the increase in thawing rates by the first occurence of a layer with a maximum refreeze of 25% of the pore water (dashed vertical lines, Figure 5). This diagnostic can be seen as a precursor for later full talik formation (i.e. year-round unfrozen conditions).

We now also discuss in section 3.2 in more detail the physical reasons for the difference in pace of thaw between the different structural units: “The outer road edge is destabilized around the year 2060 (2075 without ponding). Talik formation under the road center only occurs after year 2080, but triggers a very pronounced increase in thawing rates (Fig. 5). The large increase in late-century thawing rates under the road center are a consequence of previous continuous warming of subgrade temperatures through lateral heat flux in depth. This heat flux leads to an almost isothermal temperature depth profile under the road close to 0°C (see Fig.4, lowest panels), making the ground strongly vulnerable to further warming."

For analysing long-term consequences of climate stabilization, we have extended our model-setup and run our model under the assumption that climate will stay stationary at the end of 21st century RCP8.5 climate conditions. In Figure A3 we discuss the evolution of deep soil temperature (at 5m and at 10m depth) together with surface air warming. We now show that tiles affected by infrastructure show continuously deepening thaw depths beyond 2100, while the tundra tile shows stabilization. In the manuscript we discuss this aspect accordingly:

"We further tested how a stabilization of climate at the end of the 21st century would affect the long-term behaviour of ground thaw dynamics. All tiles which are affected by the presence of the gravel road show continuously increasing thaw depths throughout the 22nd century as deep soil layers reach above-zero temperatures. In contrast, the active layer below the tundra stabilizes at depth (Figure A3). This stabilization is realized despite slightly positive mean annual air temperatures after year 2075 (Figure A3, light blue curves) through combined effects from a pronounced reduction in snow insulation (as a consequence of strongly reduced snow heights and shortened snow seasons) and soil surface drying during summer (resulting in a strong increase in summer insulation of the soil surface). This finding shows the key impact of the protective peat layer for subground temperatures and permafrost state, but we underline that our simulated preservation of tundra permafrost also depends on the chosen model setting (e.g. with respect to external climate forcing and to internal model parameterizations)."

Revised section 4: Perspective on future modelling of Arctic infrastructure failure Our results clearly exhibit that there are combined effects from climate warming, permafrost

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degradation, and the presence of infrastructure. This highlights that future model-based risk-assessments of Arctic infrastructure should take into account all three components in understanding and quantifying the consequences of permafrost degradation on Arctic infrastructure. For such a purpose the use of numerical modelling appears the most appropriate tool to account for the full spectrum of dynamical permafrost changes expected in a warmer future.

Despite the large difference in scales between GTMs (decimetres to meters) and LSMs (hundred kilometres), our study illustrates a potential for bridging this gap by the use of Process-based tiling models (PTMs). PTMs are computationally less expensive than complex three-dimensional GTMs, structurally more flexible in describing processes relevant to permafrost degradation than both GTMs and LSMs, and adaptable to different scales. The computational efficiency of PTMs allow them to conduct long-term climate change scenario simulations while also exploring uncertainty by simulating ensembles.

In light of risk assessments of Arctic infrastructure failure, we envision two key directions of model applications: I) large-scale (i.e. LSM scale) pan-Arctic modelling of climate-induced infrastructure failure for inferring potential risk estimates, and II) fine-scale (i.e. GTM scale) modelling at individual infrastructure level to determine specific risk estimates. While large-scale modelling aims at a rather general quantification of how infrastructure could potentially be affected through climate change in certain regions across the Arctic, fine-scale modelling allows a case-specific assessment of certain infrastructures at chosen locations. PTMs can support both modelling approaches.

A) Linking PTMs to LSMs/ESMs Given the focus on large-scale risk assessments, LSM development aims at coarsely capturing general aspects of climate-change related infrastructure risks. This could be realized by implementing infrastructure through tile-based infrastructure classes, with each class representing a certain type of infrastructure (e.g. roads, pipelines, buildings). The result of LSM simulations representing infrastructure in such a reduced but therefore manageable manner (Cai et al., 2020) could produce pan-Arctic risk maps showing key regions where infrastructure failure through melting of excess ice and subsequent ground subsidence is likely for a given infrastructure class under a given scenario of future climate change. We envision three different directions of how PTMs can be linked to LSMs for modelling of large-scale infrastructure risks from permafrost degradation: (I) Drawing general conclusions from PTM analyses can support LSM development in terms of how to best incorporate tiling-based infrastructure descriptions into LSMs. For this purpose, PTMs could e.g. inform about the minimum number of structural units needed to satisfactorily simulate the interaction of a certain infrastructure type with its permafrost surrounding. Here, we showed that for a gravel road setup, four structural units (i.e. four tiles) are a sufficient approximation to describe the impacts of snow accumulation and ponding on the thermal state of the road. Other infrastructure elements will require different numbers of structural units depending on infrastructure design. (II) Rather than developing tiling-based infrastructure descriptions in the LSMs themselves, PTMs with an infrastructure component could be run offline for each LSM grid cell. This allows a quantification of pan-Arctic infrastructure risks based on the climate forcing and soil grid information (such as assumed excess ice distribution, Cai et al 2020) from a LSM, in combination with inferred permafrost-infrastructure interactions as calculated by the PTM. III) A third direction (as done in this study) is the direct use of climatological forcing data from an ESM to run a PTM in a standalone mode in which site specific aspects can be accounted for (such as local soil stratigraphy, soil moisture, ground ice distribution).

Pan-Arctic large-scale modelling as discussed above (I and II) can only provide a potential risk estimate, as they do not explicitly simulate the stability of individual infrastructure at specific locations. Site specific risk assessments must be inferred from complex three-dimensional GTM simulations which account for spatial details and therefore are capable of considering site and design-specific infrastructure aspects (such as infrastructure dimensions (Kong et al., 2019), asymmetry (Raynolds et al.,2014, Abolt et al.,2017), presence of cooling measures (Xu and Goering, 2008), and local boundary conditions (e.g. local climate, insolation angle, subgrade hydrological flow, Darrow

2011).

B) Linking PTMs to GTMs PTMs could improve GTM setups by providing information about climate-induced changes in upper model boundary conditions. GTMs often assume that the upper model boundary can be described by quasi-stationary conditions concerning atmosphere-to-ground heat fluxes (e.g. by using fixed n-factors). Darrow (2011) underlines the high sensitivity of modelled ground temperatures to upper boundary assumptions and points to limitations of using fixed n-factors when climate change effects are to be considered. In our study we show the strong enhancement effect of permafrost degradation coming from ground heat gain caused by ponding next to the road. Such effects are typically not resolved by GTM models. A model-based representation of pond formation or of snow cover changes require high vertical resolution and small time steps. Although this could in principle be represented in GTMs, the computational demand for running such models on climate timescales in very high resolution in 2D or 3D is still beyond reasonable computational effort today. In contrast, the 1D focus of PTMs on capturing vertical processes in high resolution (and with some 2 or 3D interaction) allows for investigation of complex environmental changes (and their lateral interactions) in a schematic way with moderate computational costs. This can help in drawing more general conclusions on permafrost-infrastructure interactions (under present climate and under climate change). Here we sketch three possible directions of how GTM development could profit from PTM capacities: (I) PTMs can be used to estimate how strongly changes in ground surface processes affect n-factors. This information could then be used for improving GTM model setups (by re-scaling n-factors) when climate change effects are to be considered. II) A further improved representation of upper boundary conditions in GTMs could be reached by hybrid model approaches which take advantage of the individual strengths of different model classes. One strategy could be the coupling of the complex surface energy balance component of a PTM to a GTM for use as upper model boundary forcing (“semi-hybrid approach”). (III) Such a modelling approach could be extended into a “full hybrid approach” by running the PTM on a comparable horizontal resolution as used in a GTM. The simulated thermal state from the PTM could then be applied to the GTM for calculating soil hydrology and mechanics. In turn, GTM information is returned to the PTM, such that the state of each model is updated by the results of the other in each iteration. While losing some GTMs resolution of geometries in the thermal field calculations, such an approach would benefit from the complex process description and modular adaptability of the PTM, to better describe some aspects of infrastructure degradation.

The best-suited modelling strategy will finally depend on the type of risk analysis under investigation. In the light of degrading permafrost observed already today in many regions around the Arctic, novel modeling strategies for estimating risks of future infrastructure failure under a warming climate are urgently needed.

Additionally cited studies:

Abolt, C. J., Young, M. H., Atchley, A. L., & Harp, D. R. (2018). Microtopographic control on the ground thermal regime in ice wedge polygons. The Cryosphere, 12(6), 1957–1968. Boike et al 2019 A 16-year record (2002–2017) of permafrost, active-layer, and meteorological conditions at the Samoylov Island Arctic permafrost research site, Lena River delta, northern Siberia: an opportunity to validate remote-sensing data and land surface, snow, and permafrost models

Fisher, R. A., & Koven, C. D. (2020). Perspectives on the future of land surface models and the challenges of representing complex terrestrial systems. Journal of Advances in Modeling Earth Systems, 12, e2018MS001453

Jan, A., Coon, E.T., Painter, S.L. et al. An intermediate-scale model for thermal hydrology in low-relief permafrost-affected landscapes. Comput Geosci 22, 163–177 (2018). https://doi.org/10.1007/s10596-017-9679-3

Kumar, J., Collier, N., Bisht, G., Mills, R. T., Thornton, P. E., Iversen, C. M., & Romanovsky, V. (2016). Modeling the spatiotemporal variability in subsurface thermal regimes across a low-relief polygonal tundra landscape. The Cryosphere, 10(5), 2241–

2274. https://doi.org/10.5194/tc-10-2241-2016 Kong,X., Doré,G., Calmels,F.: Thermal modeling of heat balance through embankments in permafrost regions, Cold Regions Science and Technology, Volume 158, 2019 Pau, G. S. H., Bisht, G., & Riley, W. J. (2014). A reduced-order modeling approach to represent subgrid-scale hydrological dynamics for land-surface simulations: Application in a polygonal tundra landscape. Geoscientific Model Development, 7(5), 2091–2105. https://doi.org/10.5194/gmd-7-2091-2014 Jianfeng Xu, Douglas J. Goering, Experimental validation of passive permafrost cooling systems, Cold Regions Science and Technology, Volume 53, Issue 3, 2008

Specific comments: 1) 72-74: This sentence is vague. I assume the issues referred to are related to infrastructure stability, but please be more specific.

Yes, the focus is on engineered structures, considering risks of general permafrost degradation and thaw settlement. We will specify this information in the revised manuscript.

2) 149-151: Please re-write this sentence or break it into two shorter ones.

We now broke this sentence into two shorter sentences.

3) 167-168: Please be more specific. Are you referring to improvements in subsurface physics that would allow ice lens formation to be simulated?

We refer to interactive ice lens growth as part of a beneficial future model development idea, however, the current model capacity does not allow ice to grow as ice lenses.

4) 176-178: This sentence is difficult to understand. Please consider rewriting it.

We now state: “The benefit of these developments will be implemented such that the models can help understand and quantify permafrost thaw-associated feedbacks to the climate system. Such feedbacks can only be systematically quantified using the coupled framework of Earth System Modeling, which no other models discussed in this study can represent.”

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5) 183-185: Please include a concise definition of Process-based tiling models toward the start of this paragraph, including how they differ from the virtual tiling methods mentioned in the previous paragraph.

As opposed to “virtual tiling” approaches as mentioned in the previous LSM section, we here refer to “process-based tiling” by considering tiling concepts which account for the dynamic lateral interaction between individual tiles. For avoiding confusion with different uses of terms, we now avoid the use of “virtual” and additionally shortly discuss the use of “adaptive tiling”. We have modified the text accordingly:

Section 1.2.2.: “An established LSM strategy for representing landscape heterogeneity (e.g. for. representing excess ice) consists of splitting grid cells into “tiles” to take into account sub-grid variability in surface characteristics, but such tiling schemes are not spatially explicit and do not describe interaction between tiles” Section 1.2.3: . . .”As opposed to standard LSM “tiling” approaches as mentioned in the previous section, we here refer to “process-based tiling” by considering the dynamic lateral interaction between individual tiles. Tiling approaches can be further optimized in efficiency by applying “adaptive tiling” concepts with using a dynamical number of tiles (Fisher, Koven 2020).

6) 199: Replace the phrase “pan-Arctic wide” with “at the pan-Arctic scale.” We will do so.

7) 205: Replace the phrase “we chose this region as our target region for modeling” with something like “we chose this region for our case study.” We will do so.

8) 221: Even though it’s obvious, please begin this paragraph with a simple topic sentence, such as “Although our model was designed to capture essential components of permafrost thaw, it is limited by several physical assumptions.” Also, you might consider specifying either here or in section 2.2 that your simulations are set up such that the primary driver of thaw is enhanced snow accumulation adjacent to the highway, as opposed to dust deposition or the backing up of surface flow. We will include these

suggestions.

9) 222-224: Please be more specific about how the constant bulk density of snow affects the subsurface. I assume this means that thermal conductivity is constant as Well? Thermal conductivity of snow depends on the fractions of air, water, and ice in a given snow layer in Cryogrid. Infiltration and refreezing of rain or meltwater changes the water to ice ratio and accordingly affects the effective thermal conductivity and capacity of the snow layer. We now added this information in the text: . . .”Our model represents the thermal impact of the snow cover on the ground by a simple bulk snow density approach neglecting any temporal changes in snow cover properties resulting from snow metamorphism (i.e., depth hoar) or wind compaction (i.e., ice crusts). However, the effective thermal properties of the snow layer can change following infiltration and refreezing of rain or meltwater.”

10) 236: Please define the acronym SNAP, and specify the time range for the forcing data here. We have specified the forcing data reference: “Down-scaled climate data (SNAP (SCENARIOS NETWORK FOR ALASKA and ARCTIC PLANNING, (Lader et al., 2017) was used to force our model under historical, present day and projected climate change, covering the period from 1975 to 2100.”

11) 264-265: I suggest rewording this to say “results in markedly warmer winter temperatures.” We will use this rewording.

12) 366: Consider deleting the phrase “once a critical level of ground warming has been reached,” as the first half of the sentence already references the idea of a threshold. In this paragraph, consider elaborating on when this threshold is reached. We agree on deleting the last part of the phrase. We now have analysed occurrences of talik formation for explaining the threshold behaviour (see comments above).

13) What is an “external water flux”? Is this analogous to precipitation? Or lateral flow? And does it occur throughout the spatial domain? How did you settle on the amount of 2 mm per day? By “external water flux” we describe a water flux from an

assumed adjacent reservoir which could e.g. represent a surficial water flux. This flux is only applied to the tundra and toe tiles (i.e. not to infrastructure tiles elevated above the natural tundra surface). We inferred a minimum flux value of 2mm/day to achieve closed to saturated conditions in the tundra soil. Without this additional flux, our simulated soil moisture content (which was solely determined by snowmelt, rain, and evaporation) was too dry. We now added information about our model setting accordingly: ...“We prescribe an external water flux of 2 mm day-1 for the tundra and toe tiles for the period of unfrozen soil surface conditions. This flux could mimic the impact of surficial lateral water fluxes or could be understood as a correction factor for precipitation biases. We introduce this flux for capturing observed high soil moisture conditions in tundra soils next to the road at our chosen location.”

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-192, 2020.

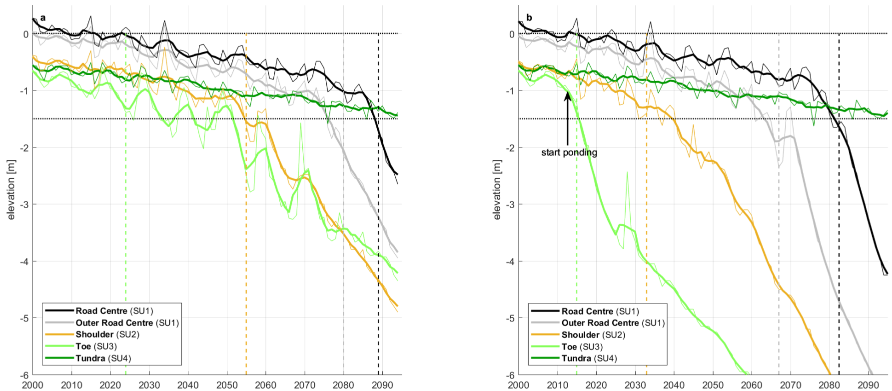

Fig. 1. Temporal evolution of maximum thaw depth (MTD)...Dashed vertical lines indicate the timing of the first occurence of a year-round partially unfrozen layer (maximum refreeze up to 25% of pore water). T

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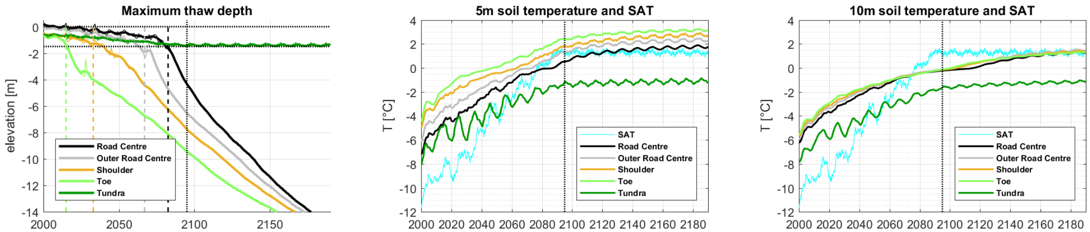

Fig. 2. Climate stabilization under RCP8.5 warming. The left panel illustrates the long-term evolution of maximum thaw depths (MTD) for all structural units for the vulnerable setting (MedRes, 5 tiles)....

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