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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 (see below). In the following we reply in detail to all the comments made:

Referee #2

General comments The context of this study is to analyze consequences of permafrost degradation on Arctic infrastructure using a model and an approach which attempts to bridge the gap between small and large scales and processes. This is useful because most global scale/land surface models cannot resolve the detail typically required for small-scale systems, such as the case of infrastructure impacts considered here. The study suggests a Process-based Tiling Model approach to bridge this gap, which attempts to capture sufficient detail but which also can be scaled up to larger LSM-scale with relative ease. The study uses measurements from a road site in northern Alaska, and involves model-based analysis of the impact the road has on permafrost thaw undergoing climate warming. The study combines methodological development with site-specific analysis in the form of a case study. This study is very relevant and should be of value for readers of TC, especially those interested in improving representation of LSMs for arctic processes. My main concern is that the PTM approach/Cryogrid is only evaluated against itself. If one of the objectives of the study is to present methodology development of the PTM approach, then a more robust evaluation and validation would be useful. Currently, different Cryogrid models are configured which are meant to correspond to simpler versus more complex conceptualization of processes, as well as finer versus coarser spatial resolution of the road-bank-tundra system. This is certainly of value and such comparisons are useful. However, since the evaluations are only conducted within the framework of the Cryogrid model, there is no external validation of the approach against other/independent models, for example models which account for higher resolutions and additional physical processes relevant at the small (100-m) scale. Hence, a validation of the approach in the strict sense is currently lacking. This makes it difficult to place the actual performance, robustness and accuracy of the Cryogrid/ PTM approach in a broader context. An evaluation/validation against a geotechnical model/GTM, or other similar fine-scale process model, would make the contribution stronger. This is important, because some process relevant at the small scale are not accounted for. These generally include consideration of later heat flux, both advective and conductive (2D), and possibly subsurface lateral flow of water (Darcy's law is mentioned, but not clear if flow can occur both in the vertical and transverse direction, as 2D flow), as well as mechanical soil deformations potentially leading to ground subsidence, which typically occur during freeze-thaw cycles. Such processes impact heat distribution in the ground. Also, only a 2D transect of the subsurface is considered, but flow and heat flux in the transverse direction (3D model) could also be relevant. Of course the ambition of the PTM approach is to avoid accounting for detailed processes/representations. Therefore, it would benefit readers to know precisely how accurate the PTM approach actually is, by comparison against a model or models which account for them. This would then more robustly support the PTM approach in being sufficiently adequate for "bridging the gap" to LSM scales.

We see the point that we do not provide a model validation in a “strict sense”. The general problem we are facing with such a validation are different model foci of GTMs (small-scale, spatial detail) and PTMs (process-oriented): GTMs often focus on describing construction specific aspects in high detail, but miss out other factors such as snow pack dynamics. PTMs on the other hand miss construction details but describe impacts from changing boundary conditions (such as a variable snow pack). Therefore, a direct comparison of results inferred from these model classes is difficult and has to be interpreted with caution. Using fully coupled hydro-thermo-mechanical GTMs requires complex parameter fitting to experimental data for appropriate model setups. Given that these models are still novel and lack experience values, large parameter uncertainties remain which further impede model comparisons. In our study we qualitatively compare our results e.g. with GTM results from Fortier et al. 2011 and Flynn et al. 2016. Both studies investigate permafrost degradation for a gravel road site on discontinuous permafrost. Despite a roughly comparable model-setup, these studies analyse a system starting from much warmer soil conditions compared to our considered continuous permafrost site at Deadhorse. Furthermore, assumptions with e.g. regard to snow accumulation and ponding differ among our studies - factors which strongly affect quantitative estimates. Differences in model-setups do

therefore not allow for a quantitative comparison. Even under identical boundary conditions, we expect that differences between our model results and fine-scale models can be large, if site-specific processes such as advective heat transport from lateral water flow are considered only in one model setup. We therefore further stress in the revised manuscript the need of using fine-scale models for a site-specific risk assessments (we do not recommend to do such an assessment with using a PTM, see revised section 4 below, end of general comments reply).

In the revised manuscript, we now also have included more aspects for a qualitative check of our results and cite additional GTM studies. Further, we now discuss in more detail the physical processes which determine the degradation dynamics (see comments to reviewer 1). We also added additional information in the model description section to underline which processes are captured in our model, and which processes are missing. In short reply to the points raised above, this concerns: Lateral heat flux and subsurface lateral flow of water

Our version of Gryogrid3 describes conductive vertical and lateral heat flux between tiles and describes vertical and lateral water flux. Yet our model does not describe the effect of heat advection from water flow which is subject for further model development. We do not consider the omission of modelling advective heat transport critical for our considered case here, as we focus our discussion on the timing when ground thaw reaches the subgrade underneath the embankment for the first time. Advective heat transport will increasingly become important at later stages of permafrost degradation when pathways of subsurface flow will develop and contribute to higher rates of degradation. If our focus was on modelling a gravel road on warm, discontinuous permafrost, advective heat transports effects are likely to play a much more important role for near-term permafrost degradation.

3D flow and heat flux

We have constrained our model setup to an idealized 2D linear infrastructure case to capture the dominant road-permafrost interactions stemming from snow-free conditions at the road center, snow accumulation on the shoulders, and ponding at the toe. In reality, the thermal regime of a road can be affected by factors requiring a 3D model setup. In our revised manuscript we underline the need for GTM modelling to capture such effects (see new section 4), but an explicit modelling of 3D features with Cryogrid would go beyond the applicability the model is designed for.

Also, some of the details of the implementation of the model could be clarified. For example, the ponding feature in the model needs clarification, please see comments below. This is especially important considering its impact on results, for example Fig 5. Also, the implementation of effective thermal conductivity could be clarified, specifically if/how the dynamic phase state of water, as ice or liquid, filling the pore space is accounted for in the subsurface, or if only a static thermal conductivity of the different materials (shown in Table 2) is considered.

We now give more details for the implementation of ponding in the model set-up section (2.2): . . .”Pond formation has a pronounced effect on our modeled soil temperatures by altering surface energy fluxes through lowering surface albedo and replacing thermal properties of the soil surface by those of a water body.” We now also specify the albedo value of a water surface (0.07) in table 2.

Effective thermal conductivity is calculated in the model at each time step depending on the soil constituents in each layer - i.e. the fractions of mineral/gravel and organic, water and/or ice fraction, and air. We now added the information about calculation of effective thermal conductivity and capacity in the legend of table 2: ...Effective thermal conductivities and heat capacities of each layer are calculated based on the volumetric fractions of the ground constituents water, ice, air, mineral, gravel, and organic (Cosenza et al.,2003;Westermann et al., 2013).

Latent heat effects through phase change are explicitly considered when modelling heat diffusion with Cryogrid.

Further, the presentation would benefit from an explanation of what the advantage of the approach is compared to using, for example, a GTM at the small scale which is forced/driven by boundary conditions obtained from an LSM? This is essentially what is being done in this study. Hence, infrastructure impacts could, at least in principle, be modeled that way by combining large and small scales using different models, and hence without bypassing fine-scale processes and their effects. Perhaps this is the intention of the discussion in Section 4; if so, that section could use clarification, please see comment below.

Based on the comments made by both reviewers, we have strongly revised section 4 for substantiating our proposed strategy of combining PTMs with LSMs and GTMs.

Revised section 4:

Perspective on future modelling of Arctic infrastructure failure

Our results clearly exhibit that there are combined effects from climate warming, permafrost 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. L 106-107: There are other lateral processes which also impact permafrost change and thaw, especially subsurface lateral processes such as flow of water and associated advected heat flux, both for 2D and 3D model representations.

We wanted to give a few examples of lateral processes and now added the aspect of subsurface water flow.

L 110: It is not entirely clear what a "conservative assessment" means in the context of "permafrost thaw impacts". If models are conservative in their assessments of the impacts of permafrost thaw, then one would assume they are over-estimating thaw rates. Perhaps this part could be rephrased/clarified.

We now rephrased this sentence: Thus, current model assessments are most likely underestimating permafrost thaw impacts,...

L 129-130: There are several other studies on modelling polygonal tundra dynamics, please consider citing.

We now also cite Pau et al. (2014), Abolt et al. (2018) and Kumar et al. (2016)

L 180-190: Are there any other PTM models other than Cryogrid, if so please consider Citing.

We now also mention work by Jan et al. (2017) in which the authors used a mixed dimension model structure for efficiently simulating surface/subsurface thermal hydrology in low-relief permafrost regions at watershed scales, as well as work by Daanen et al. (2011), in which the authors used the GIPL model for linking large scale climate and permafrost simulations to small scale engineering aspects with a focus on Greenland. We are not aware of further permafrost models being of comparable flexibility and model complexity to Cryogrid.

L 245: Vulnerable case, ponding – please explain/clarify exactly how ponding is represented in the model and what effects it has. Does this impact the SEB? Enable infiltration of water from the surface, as a source? Does it impact thermal properties, is effective thermal conductivity considered at the surface-subsurface interface? Etc.

Yes, pond formation changes the SEB in our model pronouncedly. We now clarified this aspect by adding the following sentence after L245: “...Pond formation has a pronounced effect on our modeled soil temperatures by altering surface energy fluxes through lowering surface albedo and replacing thermal properties of the soil surface by

those of a water body.”

We extended table 2 to include the information about our assumed albedo of a pond (0.07). In the model result discussion (section 3.2) we now also mention the effect of ponding on heat uptake: . . .” Further, a pond allows for a more efficient heat uptake through vertical mixing within the water column as compared to top-down heat diffusion in solid ground.” In the model description section, we now added information about modelling ground subsidence and ponding (with a reference to the work in which the ponding/subsidence scheme is discussed in detail): ...The model explicitly simulates ground subsidence and subsequent ponding as a consequence of melting of excess ice in the ground (Westermann et al., 2016).

Section 2. Model setup, boundary conditions. Would be useful to mention here that the model depth is 1000 m (if this indeed is the case), this is "hidden away" in Appendix A3. The reason being a thin model domain of only approx 10 m (as Fig 3 and 4 depict) would most likely incur boundary effects from the base boundary condition.

To avoid misinterpretation of our vertical model domain extent, we now specify our lower model boundary in the model-setup section in the main text: “...We used a high vertical resolution for grid cells in the upper 4 meter of the ground and coarse resolution towards our lower model boundary at 1000 m depth, which is subject to an assumed geothermal heat flow of 0.05 W m-2 (Lachenbruch et al., 1982).”

Section 3/Figures 4,5: It would also be nice to see/visualize the boundary conditions which are used to drive the model, if possible, for example the forcing/driving conditions at the surface. This can help understand and interpret the results shown in these Figures.

We now show in a new Supplement Figure (see Fig.2, reply to RC1) the time evolution of the forcing surface air temperature. The forcing shows a gradual increase in surface temperatures which does not explain the thaw dynamics illustrated in Figure 5. When interpreting thaw trajectories in section 3.2, we now refer to the forcing evolution and focus our discussion on the issue of talik formation (see comments made in response to reviewer 1).

Section 4. The model and approach used in this paper is very nice and clearly relevant, but the purpose of this section is not so clear. It would be far more informative and convincing to actually demonstrate the strategy for the different applications suggested here. For example, can a demonstration of a model linking to LSMs beyond the 100-m scale modeled here be made? Also, the discussion on suggested analysis for risk assessment from line 350 onwards would have more substance if a demonstration could be made.

We have completely revised section 4 to discuss the linkage of PTMs with LSMs and GTMs and now discuss more concretely how a combined modelling strategy could be achieved (see new section 4).

Fig 4: Consider making a note that the vertical extent (elevation) of the model domain is not depicted here, could refer to Appendix A3. Also in Fig 3, the extent of the model in the vertical direction is depicted only as around 10 m, but according to A3 is 1000 m.

We now state in the legends of Fig.3 and Fig.4 that the lower model boundary is at 1000m to avoid misinterpretation of the extent of our vertical model domain.

Fig 6: Please improve clarity, font sizes and legends are relatively small.

We will improve readability of the figure.

Table 2: Hydraulic properties are not described; what is the hydraulic conductivity or permeability, and porosity, of the different materials used? Typically, there is great variability and hence uncertainty in hydraulic conductivity and this greatly impacts water Flow.

We use a constant hydraulic conductivity of 1e-5 m/sec for all soil types. We now added this information in the parameter table. We do not resolve differences in hydraulic conductivities between the natural tundra ground and the subgrade material. As our considered model site does not provide conditions for large lateral subsurface water flow, we expect comparatively small lateral water exchange rates a realistic description. Porosities for the individual soil and embankment layers are given in table 1.

Table 2: Do the thermal conductivities refer to dry porous media? How is effective thermal conductivity, accounting for phase state of water-ice in the porous media, calculated?

Effective thermal conductivity of each layer is calculated based on the volumetric fractions of the ground constituents water, ice, air, mineral, gravel, and organic (Cosenza et al.,2003; Westermann et al., 2013). The temperature dependence of the effective thermal conductivity is taken into account by calculating temperature-dependent water and ice contents. We now added this information in the table legend of table 2.

Table 3: Is there a 'conservative' setting for the HighRes model setup? Please clarify.

We now added the information in table 3 that for the HighRes model setup no conservative setting was run.

Fig A2: What do the model ranges, min to max, with median, refer to here? What is changed between the "Cryogrid model runs" to get the ranges of results? Please Clarify.

The indicated min-max range illustrates the spread of estimates, each inferred from 11 individual simulations years, covering the period 2010 to 2020. The years are subject to differing climatological input. We now have re-formulated the figure legend to clarify this issue: ..."Blue dots and blue lines illustrate simulated year-to-year variability and indicate the median and min-max range estimated from 11 snow seasons simulated by CryoGrid3 for the period 2010 to 2020,..."

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