Dear Reviewer,

we thank you very much for your comments which will help to increase the quality of our manuscript. Please find in the following a point-by-point reply to your review. We furthermore provide the revised version of our manuscript as well as an "change-tracked" version in which individual changes with respect to the submitted manuscript are highlighted.

Your comments are in **bold** and extracts from the manuscript are in *italics*, changes to the manuscript are highlighted *yellow*.

> **This paper presents novel model developments to account for effects of ice-wedge polygon formations in permafrost regions. The scheme is a tile-based approach applied to the CryoGrid3 Land Surface Model which is evaluated against data from a field site in the Lena River delta, and then effects of different hydrological conditions are investigated. The paper is well written, clear, highly relevant and generally complete. However, some details of model need further clarification, and some aspects of the study can be improved, which should only require moderate effort to address.**
>
> **Clarifications are needed regarding what is actually meant by micro-topography in the context of the model implementation. The tile-based approach, although elegant, is nonetheless representing a multitude of polygons as a single aggregated, effective polygon system. This means many effects of micro topography within the grid cell are averaged out. This may cause confusion because micro topography effects may be interpreted to refer to the dynamics actually occurring within and between individual polygons in a cluster. This scale of the dynamics does not appear to be represented by the tile-based approach.**
>
> We clarified our notion of "micro-topography" in section 2.2.1 which introduces the tiling approach as referring to the partitioning of polygonal tundra into centres, rims, and troughs:
>
> *We subdivided the polygonal patterned landscape into three landscape units according to what we refer to as its "micro-topography": polygon centres (C), elevated rims (R), and a network of troughs (T) that spreads between the distinct polygonal structures (Fig. 2, B).*
>
> We furthermore stated the approach of a single "effective" polygon being representative for a larger area containing several polygons more precisely.
>
> Removed from section 2.2.1:
>
> ~~*Note that together these tiles represented entire areas of the landscape consisting of multiple polygons, and not just a single polygon.*~~
>
> Added to section 2.2.1:
>
> *Note that apart from the partitioning into centers, rims, and troughs, our approach does not take into account topographic features of individual polygons. Instead, we assumed that larger areas with multiple polygons of similar topography and subject to similar hydrological conditions, can be described via single "effective" polygon composed of the three tiles.*

Also, it is not clear if/how the scheme can be used for clusters with initially mixed HCP/ICP/LCP polygons, which might be relevant for regions where the intended spatial discretization scale of the LSM encompasses two or all three of the polygon categories.

As discussed in the article (section 5.4.1) our study aimed at an improved process-understanding and a proof-of-concept for the tiling approach applied to polygonal tundra. In particular, we addressed potential issues of applying it in a straight-forward way to represent entire grid cells of LSMs/ESMs containing polygonal tundra. In the revised manuscript we extended this discussion by pointing also to the problem of various polygon types within one grid cell:

While both studies demonstrated the capabilities of the tiling concept, they also shed light on the remaining difficulties of the implementation and the up-scaling of this concept within ESMs. The latter comprise the spatial variability of hydrological conditions and the initial presence of different polygon types within one grid cell. Combining the tiling approach with ensembles of simulations might constitute a possibility to bridge this scaling gap.

Treatment of water flow is rather simplistic. Groundwater flow is greatly affected by hydraulic conductivity, which is notoriously heterogeneous and varies greatly for different textures and is also challenging to estimate in the field. The value for K shown in Table 2 is quite large and seems to be taken for granted. No uncertainty or error estimate is provided, which is unusual for hydraulic conductivity measurements. A parameter sensitivity study for K would therefore be useful and could provide more insight to the impact of hydrological flows, and in turn, their potential impact on soil T, WT, etc. in the polygon formations.

In our model the hydraulic conductivity K is a parameter used to quantify the lateral water fluxes between adjacent tiles, according to Eqn. (6). We chose a value which was at the lower end of the values provided in Boike et al. (2018) for the uppermost soil layers, ranging from $1.09*10^{-5}$ m/s to to $46.3*10^{-5}$ m/s. We added the range of values for K to the revised manuscript.

The saturated soil hydraulic conductivity (K) between all connected tiles was set to $1\cdot10^{-5}\ m\ s^{-1}$ *and the reservoir hydraulic conductivity* (K_{res}) *was set to* $5\cdot10^{-5}\ m\ s^{-1}$ *both values were of the same order of magnitude as the various estimates for the uppermost soil layers in the same study area* ($1.09–46.3 \cdot 10^{-5}\ m\ s^{-1}$ *; Boike et al. (2018)).*

We furthermore revised the model validation (section 3) such that the influence of the individually varied parameters becomes apparent. We complemented the parameter variations in the initial manuscript (rim elevation e_R, areal fraction center γ_C, snow density ρ_{snow}) by variations of the field capacity (θ_{fc}), and the saturated hydraulic conductivity (K). For K we changed the value from the default of $1\cdot10^{-5}\ m\ s^{-1}$ to a smaller value of $1\cdot10^{-6}\ m\ s^{-1}$. Both the modelled evolutions of ALT and WT turned out to be quite robust against variations of K (see Figures in section 3 of the revised manuscript).

Since the model validation was completely revised, we modified some formulations in sections 3.1 and 3.2 which are highlighted in the “change-tracked” manuscript provided together with the revised manuscript.

The assumption of near-instantaneous/rapid vertical water flow might be overly simplistic. (Section 2.2.3, Fig 3). Although hydraulic conductivities of upper soil horizons applicable to the active layer may be high, unsaturated flow is largely dictated by non-linear soil moisture retention curves. Even a small change below saturation can lead to a large decrease in hydraulic conductivity, for some textures by several orders of magnitude, thereby yielding very slow flow rates. Thus, the rapid vertical water flow assumption may be questionable. This may be important because water flow can carry heat through advection, both vertically and laterally, and if near-instantaneous infiltration is assumed, overly non-conservative heat advection may result.

We agree that the employed hydrology scheme assuming instantaneous infiltration is rather simplistic. We are still confident that it was sufficiently suited to fulfill the purpose of reflecting the spatial heterogeneity of the ground hydrological regime of polygonal tundra. Moreover, Zhang et al. (2010) showed that instantaneous infiltration algorithms do not necessarily perform worse than more sophisticated schemes. To stress this limitation of our model we complemented the model description in section 2.2.3 by the following formulations:

We note that the employed hydrology scheme is rather simplistic compared to other schemes available (e.g., Painter et al. (2016)). However, it constitutes a significant improvement compared to the previous version of CryoGrid3 (Westermann et al., 2016), which did not take into account variable water contents in the active layer at all. We confirmed that the employed scheme, in combination with the lateral water transport scheme detailed in Sect. 2.2.4, was sufficiently suited to reflect the spatial heterogeneity of the subsurface hydrological regime of polygonal tundra (see Sect. 3).

Regarding the concern about overly non-conservative heat transport, we would like to clarify that in the employed version of CryoGrid3, the process of heat advection is not taken into account. This means that infiltrating water only changes the soil thermal properties and may potentially release latent heat during freezing, but has no direct effect on the temperature of the grid cells. We added the following sentence to section 2.2.3 of the revised manuscript:

Note that no sensible heat is transported with the infiltrating water, i.e., the process of heat advection is not taken into account by CryoGrid3.

Results, eg Fig 13: The system behavior is greatly controlled by the external boundary condition (the external reservoir). How realistic is this as a BC? A natural hydrological BC is the catchment boundary which would typically be considered no-flow for water, and then internal features such as lakes/reservoirs would be dynamic, resulting from mass and energy balances including surface and subsurface flows in the catchment. I understand the reservoir concept is used in the study to investigate effects of different hydrological conditions, but it seems this is a somewhat artificial constraint inherent in the model.

The external water reservoir used to reflect the site-specific hydrological conditions indeed turned out to exert a strong influence on the system. We used this artificial boundary condition to reflect contrasting drainage conditions between different parts of our study area (e.g., waterlogged center versus drained margins of Samoylov Island). This boundary condition is a reasonable assumption for our study area (which is mainly flat with no pronounced catchment topography) and objectives, it may be less suited for other study areas, where a coupling to the catchment hydrology would be desirable. We would still like to point out, that via the two parameters (reservoir conductivity and reservoir elevation) the reservoir boundary condition allows a great flexibility. By making the reservoir conductivity dependent on the degree of degradation, one could also reflect the increasing hydrological connectivity of polygonal tundra with ice-wedge degradation. We discussed these limitations in more detail in section 5.4 of the revised manuscript:

The model setup used in this study makes idealized assumptions on the hydrological connectivity and the hydrological boundary conditions of the polygonal tundra. The connectivity of inter-polygonal troughs which we assumed to be given throughout the simulations, might in reality only develop with advancing degradation of ice-wedges. The assumption of a static external reservoir proved to be useful for comparing contrasting hydrological conditions, but is an idealization which neglects the hydrological dynamics of the surrounding terrain. However, if specific study cases (opposed to our idealized test cases) would require the above-mentioned processes to be taken into account, these could readily be implemented within the CryoGrid3 model framework.

Heat flow, Section 2.2.4, Eqn 4 and B1. Eqn B1: How is the thermal conductivity of individual tiles at cells i obtained? (k_alphaˆi and k_betaˆi) Are they a function of the thermal properties of water and ice and soil grains (Table D1, but not apparent in equation B1)?

The thermal properties of each soil (and snow) grid cell are calculated based on their composition of their constituents (mineral, organic, water, ice, and air). This is detailed in Westermann et al. (2013), which has been added as a reference. In the revised manuscript we added the heat conduction equation which explicitly contains the thermal properties to the model description and referred to Westermann et al. (2013) for details on the calculation of the thermal properties. This modification should also clarify how the thermal conductivities in Equations 4 and B1 were obtained.

Added to section 2.2.2:

The numerical model simulates the temporal evolution of the ground temperature profile (T (z)) by solving the one-dimensional heat conduction equation, taking into account the phase change of water through an effective heat capacity:

$$\left(C(z,T)+\rho_w L_{\mathrm{sl}}\frac{\partial\theta_{\mathrm{w}}}{\partial T}\right)\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(k(z,T)\frac{\partial T}{\partial z}\right) \quad ,$$

where θ_w is the volumetric water content, ρ_w the density of water, and L_{sl} the latent heat of fusion of water. The thermal properties of the soil cells are (volumetric heat capacity C(z, T) and thermal conductivity k(z, T)) are derived from the volumetric fractions of mineral, organic, water, ice, and air (see Westermann et al. (2013) for details).

P11 L19-21: Dry insulating layer – how is this represented in the model? Specifically, how does moisture and air (dryness) influence the thermal properties?

I note thermal conductivity of air (or vapor) is not listed in Table D1, nor apparent in eqn B1. See also questions above.

See answer above and Westermann et al. (2013). We added the assumed value for the thermal conductivity of air (k_a=0.0243 W/(mK)) to Table D1.

P7 L14-21, Fig 2: Does this mean that all troughs of all polygons are perfectly connected, leading to the same dynamics for all polygons in the grid? Also e.g. Section 2.3.2, Section 2.3.6 – Micro topography is not really represented, it seems all polygons are represented by an single effective polygon-rim-trough system. There is no variability in the dynamics within the multiple and generally diverse polygons as depicted in Fig 2a and 2b.

It is correct, that for a simulation with a specified water reservoir, all polygons are represented via an effective polygonal structure, which assumes a perfectly connected network of troughs. A poorly connected network of troughs could be realized by assuming a smaller value for the "reservoir conductivity" K_{res}, which was, however, not investigated in this study. For the clarification of our notion of "micro-topography" we refer to our answer to your first point and the respective changes to the manuscript.

P11 Section 3.1: Good that full details of the data set is cited but it would help us to know briefly how extensive the data set is, especially how many vertical profiles measuring soil T, moisture, WT etc., exist for each of the different micro-topographic units of the polygonal tundra site. Or is there only one vertical profile per unit type (polygon center, rim, trough)?

The dataset contain one profile of soil temperature and soil moisture for each topographic unit (center, slope, rim, "ice-wedge") and the water table record from one adjacent polygon centre. We added these details to section 3.1:

This dataset contains vertical soil temperature and soil moisture profiles of different micro-topographic units of the polygonal tundra (one profile for center, slope, rim, and "ice-wedge", respectively; see Fig. 1 for the location of the measurement polygon), as well as water table (WT) records for an adjacent polygon centre.

Not clear what statistics the error bars represent in e.g. Fig 5 and others. Are these statistics over multiple profiles for each site type, or measurement error, etc.?

The error bars in Fig. 5 represent the standard deviation of the active layer depth measurements of the CALM grid on Samoylov for the respective category (39 measurement points for polygon centers, 80 measurement points for polygon rims). We added these details to the manuscript in section 3.1 and the caption of Figure 5.

Added in section 3.1:

We also used the active layer thickness (ALT) time series from the Samoylov Circumpolar Active Layer Monitoring (CALM) site which cover different micro-topographic units of polygonal tundra, including polygon centres ("wet tundra", n = 39 measurement points) and rims ("dry tundra", n = 80 measurement points) (Boike et al., 2013).

Caption of Figure 5:

The black markers represent the means and standard deviations of categorized CALM data (n = 39 measurement points for centers, n = 80 for rims) described in Boike et al. (2018).

P6 Eqn 4: Please clarify what cells i refer to, e.g. vertical discretization.

We changed the formulation in section 2.2.4 to:

The lateral heat flux between adjacent tiles is computed for each cell of the vertically discretized grid of all tiles, according to Fourier's law. The heat flux $q_{\alpha,i}$ *[J* s^{-1}*] to the cell with index i of tile α from all adjacent tiles is given as ...*

We furthermore specified in section 2.2.4 when the lateral heat fluxes are applied:

The lateral heat fluxes are added after each lateral transport timestep Δt_{lat} *to the vertical heat fluxes resulting from heat conduction and boundary fluxes (i.e., geothermal and ground heat fluxes).*

P7 Eqn 5 and Eqn 7: There is no cells i notation in the Darcy formulations, is this intentional?

As mentioned in Sect. 2.2.4 the lateral water fluxes are calculated as bulk fluxes (rather than cell-wise). They are applied using the instantaneous infiltration scheme which is also used for vertical routing of water. To clarify this, we added the following sentence to section 2.2.4:

The bulk lateral fluxes q_α *are applied to each tile α after each lateral transport timestep* Δt_{lat} *using the instantaneous infiltration scheme described in Sect. 2.2.3.*

P27 Eqn A1: Seems "1" should be cell index "i" to be consistent, typo?

The "1" refers to the uppermost grid cell of the subsurface which is indexed with 1. We changed the explanation of the symbols in Appendix A so that they refer to this cell rather than to cell "i".

The rainfall is obtained from the forcing data and is initially put into the uppermost cell (index 1) of the discretized soil grid:
...
where $\delta\theta_{w,P}^{1}$ *denotes the change of water content in the uppermost cell due to precipitation, p is the precipitation rate ([m s−1]), Δt is the timestep ([s]) and* Δ^1 *the height of the uppermost cell ([m]).*

We hope that we were able to address all questions and comments raised in your review to your satisfaction, and that our revised manuscript is in an adequate state for publication.

Yours sincerely,

Jan Nitzbon (on behalf of the authors)

References

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