

Comments review 1

We sincerely thank the reviewer for the thoughtful and constructive comments, which will help make the manuscript more valuable. We have addressed all the comments below and will improve the manuscript as suggested. The reviewer comments below are numbered with “RC#”: and shown in bold font, while authors’ comments start with “AC#”.

The manuscript is well written and provides a valuable proof of concept for representing ice-rich permafrost landscapes in CLM5. The comments below are intended to strengthen the manuscript and clarify several questions regarding the model formulation, interpretation, and potential broader applicability.

This manuscript presents a novel two-tile, dynamically coupled representation of ice-rich permafrost landscapes in CLM5. Rather than representing the vegetated portion of a grid cell as a single, uniform soil column, the authors divide it into elevated and lower landscape tiles that exchange snow, lateral heat, and lateral water. The two tiles can differ in soil stratigraphy, excess-ice content, snow cover, moisture regime, and elevation, while excess-ice melt allows subsidence and changes in relative topography over time.

RC1: The approach is a useful and promising step toward representing thermokarst-related heterogeneity in an Earth system modeling framework. However, the manuscript should clarify how tile-resolved state variables and fluxes are aggregated back to the land-unit or grid-cell scale for coupling with the atmosphere, river-routing scheme, and, ultimately, carbon-cycle calculations. It is not yet clear whether aggregation is simply area-weighted, how conservation is ensured across tiles, or how variables with different vertical structures and surface elevations are reconciled.

AC1: Most of the aggregation is done using area weighting, as the tiles are treated the same way as standard columns in CLM.

Vertical structure is resolved explicitly only when necessary, according to the excess ice implementation described in Lee et al., 2014. Virtual, non-permanent variables representing extended soil-layer thickness due to excess ice, are calculated when variables that depend on vertical soil structure, such as soil temperature, are calculated. For other calculations, standard vertical structure is used.

Conservation is maintained for flux variables such as lateral water flux. Water is added to one tile and removed from the other, such that the total amount of water is conserved. Lateral water is also included in the water balance check.

We will add a section to the manuscript describing the aggregation procedure and include a table in the appendix summarizing how different variables are treated.

RC2: At present, the paper demonstrates improved representation of soil physical processes rather than improved projections of greenhouse-gas emissions. Carbon, methane, nitrogen, vegetation, and dynamic ecosystem feedbacks are intentionally left for future work. Given the broader motivation of reducing uncertainty in permafrost-carbon feedbacks, the discussion would benefit from a clearer outline of how this framework could be extended to biogeochemistry and eventually scaled to circumpolar applications.

AC2: We agree that the potential extension to biogeochemical processes should be discussed more clearly. The implementation is compatible with the biogeochemistry module and has already been tested with the biogeochemistry module enabled and in global simulations.

For future biogeochemistry analysis, the model will be run with the biogeochemistry module enabled and with a longer spin up to establish realistic conditions for carbon-related state variables

such as soil carbon content. Existing carbon measurements from Iskoras and Samoylov will be used for model calibration and evaluation on a site scale.

The implementation also works on a global scale and ideas about upscaling to regional or circumpolar uses existed.

We will add a discussion of potential extensions for biogeochemical and global uses to the manuscript. See the end of the document for proposed additions.

RC3: Several key inputs remain site-specific and partly prescribed, including tile area, contact length, inter-tile distance, initial elevation difference, soil profiles, and the partitioning of excess ice between tiles. This is entirely reasonable for a site-scale proof of concept, but the manuscript should discuss how these parameters could be derived from observations, remote sensing, landform maps, or statistical parameterizations at regional and global scales.

AC3: We agree that the site specific parametrization is an important limitation for global applications. But several of the variables required for the subgrid-scale study need to be determined at a high spatial resolution. These information can be obtained from field studies or drone-measurements, and are therefore limited to small sites.

For applications at larger spatial scales, statistical approaches could be used together with additional information, from remote sensing products. For example, information about the extent of the pattern landscape. The approach is mainly intended for patterned landscapes, in which structures of similar size occur repeatedly. Consequently, characteristic parameters derived for different landscape types or regions could potentially be used to develop statistical parameterizations for regional applications.

High-resolution measurements of ground elevation, for example from LiDAR data, could also be used to derive characteristic elevation differences and structure sizes for specific areas. These parameters could then be used to inform the initial configuration of the tiles.

We will add a discussion of these possibilities and the challenges associated with upscaling to the manuscript. See the end of this document for the proposed addition

RC4: Forcing uncertainty also remains an important limitation. At Samoylov, simulated snow depth is generally too high, and winter soil temperatures are correspondingly too warm. At Işkoras, the Mire retains permafrost despite being permafrost-free in reality, possibly because of cold biases in the forcing and/or overly strong thermal insulation in the prescribed peat profile. These mismatches do not undermine the value of the tiled approach, but they should be more explicitly considered when interpreting the apparent success of the model.

AC4: This is a valid point. We will add an extended section to the discussion, where we discuss in detail the limitations of the modeling approach and uncertainties related to the forcing data, see end of document.

RC5: The two-tile framework is an elegant simplification, but real thermokarst landscapes often comprise more than two interacting elements, including rims, polygon centers, troughs, ponds, drainage pathways, peat plateaus, collapse scars, and lakes. Future work should evaluate whether two tiles are sufficient across different degradation stages and landscape types, or whether selected environments require additional tile classes or an adaptive tiling structure.

AC5: Previous studies have used multiple tiles to represent thawing polygons and peat hills. The two tile approach was chosen because it is simple enough to be included in an ESM and used for global simulations without using too much additional computational resources. It represents the main parts of those structures. Multi-tile frameworks will probably be too computationally intensive to run on a global level. For soil physics in the chosen landscapes, the two tile approach seems

sufficient. Future work, with biogeochemistry or global simulations, will also discuss whether two tiles are enough for all such landscapes and applications or specific cases require multiple tiles.

RC6: The three research questions posed in the Introduction are addressed through the results and sensitivity experiments. Nevertheless, the manuscript would be strengthened by a brief, explicitly structured synthesis in the Discussion or Conclusion that addresses each question in sequence and distinguishes robust general findings from site-specific or forcing- and parameter-choice-sensitive conclusions.

AC6: We agree that a more explicit synthesis of the research questions would strengthen the manuscript. We will add a structured discussion, addressing the research questions where we also distinguish general findings from site specific conclusions. See the end of this documents for a proposed discussion.

RC7: The lateral water-exchange scheme also deserves further discussion. In the current formulation, lateral water transfer is driven by differences in perched water-table elevation between the two tiles. This is a reasonable first-order approximation, but it conceptualizes the system as two adjacent vertical columns connected through a relatively simple conductance term.

Previous work by Harp et al. and Zlotnik et al. suggests that drainage from inundated low-centered polygons is spatially heterogeneous rather than uniformly distributed across the polygon center. Much of the lateral subsurface drainage may occur through a relatively narrow annular zone near the polygon rim. Their analyses further indicate that drainage depends on polygon geometry, seasonal thaw depth, hydraulic anisotropy, and hydraulic resistance at the polygon center–trough interface. Incorporating these controls into the lateral-flow parameterization could improve the physical realism of the Samoylov application and provide a useful pathway toward representing transitions between ponded low-centered polygons and more efficiently drained polygon states.

Harp, D. R., Zlotnik, V., Abolt, C. J., Busey, B., Avendaño, S. T., Newman, B. D., Atchley, A. L., Jafarov, E., Wilson, C. J., and Bennett, K. E.: New insights into the drainage of inundated ice-wedge polygons using fundamental hydrologic principles, *The Cryosphere*, 15, 4005–4029, <https://doi.org/10.5194/tc-15-4005-2021>, 2021.

Zlotnik VA, Harp DR, Jafarov EE, Abolt CJ. A Model of Ice Wedge Polygon Drainage in Changing Arctic Terrain. *Water*. 2020; 12(12):3376. <https://doi.org/10.3390/w12123376>

AC7: We agree that drainage in polygon landscapes is complex compared to the approximation used in the approach. Drainage is strongly linked to drainage channels across polygons. Incorporating additional controls on drainage or combining the current approach with the approaches described in previous studies and tested at Samoylov would probably increase representation at Samoylov.

However, an important object of the paper was to present an approach that works for different landscape types and has the potential to be upscaled to regional and global applications. Incorporating complex control mechanisms would make upscaling difficult, as it would require even more parameters and probably only improve simulations for polygon landscapes.

We therefore chose a relatively simple approach (which also just includes 2 different tile two different tiles instead of 3 three). This provides a balance between physical realism and computational efficiency while retaining the main processes relevant to the landscape types investigated in this study.

We will include a small section in the paper, where we discuss more carefully why we chose the rather simple approach.

We will add a Discussion to the manuscript where we will discuss the points mentioned above:
See the intended extension of the manuscript below.

Discussion:

This manuscript presents a new implementation in the CLM5 model for representing microtopographic structures in permafrost environments. The approach was evaluated with respect to three research questions.

1. Can ice-rich polygonal tundra and peat plateau landscapes in permafrost regions be realistically represented in CLM5 using dynamically coupled tiles?

The results demonstrate that a tiling approach allows the representation of two distinct landscape units characteristic of ice-rich polygons and peat plateaus. The approach reproduces realistic differences in soil temperature, soil moisture and snow conditions between the tiles. Importantly the approach also captures longer-term landscape dynamics, including the degradation and melting of excess ground ice. For the palsa landscape, the tiling approach reproduces a stabilization effect of the palsa that is consistent with observations. Palsas remain relatively stable until the beginning of the 21st century, whereas standard CLM simulations indicate onset of palsa collapse as early as 1980.

2. How does the tiling approach influence soil temperature, active layer thickness, and soil moisture dynamics?

The tiling approach generates two different soil physic regimes; a cold and dry tile, with a comparatively stable ALT and a warmer and wetter tile. Compared with standard CLM, one tile becomes colder and drier, while the other is warmer and wetter. This differentiation is important because it allows the model to represent the strong sub-grid-scale contrasts in thermal and hydrological conditions that characterize patterned permafrost landscapes.

3. Which process exerts the strongest control on soil physical conditions and permafrost stability?

The sensitivity analysis indicates that snow redistribution exerts the strongest control on soil temperature and permafrost stability. Changes in snow distribution strongly affect the insulation of the ground during winter and consequently influence the thermal regime of the underlying soil.

Although the approach shows robust results for the general representation of patterned permafrost landscapes, reproducing site specific conditions remains challenging. Simulated snow depths at Samoylov are too high, and the mire at Iskoras remains cold enough to maintain a deep permafrost layer, that is not observed at the site. Both of these flairs are due to errors in forcing data. They could potentially be reduced through site-specific correction and calibration of the forcing data. Thus, while the presented approach demonstrates the ability to represent the characteristic physical dynamics of patterned permafrost landscapes, its application for quantitative site-specific predictions requires sufficiently accurate local forcing data.

The primary objective of this study is not to reproduce every site-specific detail, but to demonstrate that the tiling approach can simulate fundamental physical processes associated with patterned permafrost landscapes and model the distingue landscapes parts.

Previous studies used multiple tiles to represent polygonal landscapes. In the present study, a relatively simple two-tile configuration was deliberately selected to limit computational costs and facilitate future upscaling to circumpolar applications. For the representation of the dominant soil physical contrasts, the results indicate that two tiles are sufficient. Future work, with

biogeochemistry or global simulations, will also discuss whether two tiles are enough for all such landscapes and applications or specific cases require multiple tiles.

Previous studies have further indicated, that lateral water flux in Samoylov is highly dependent on a system of drainage channels through the rim and in cooperating such control mechanisms would most likely improve simulations at Samoylov. However, such control mechanisms would require additional site-specific parameters and would be less suitable for potential circumpolar applications. Therefore, a comparatively simple lateral water exchange scheme based on the perched water table was adopted in this study. This represents a compromise between physical realism at individual sites and the simplicity required for broader-scale applications.

The model approach has also been tested with the biogeochemical module enabled and has produced promising preliminary results. A detailed analysis of these simulations, however, is beyond the scope of the present study. Future work will focus on carbon dynamics, by conducting simulations with the biogeochemistry module enabled and calibrating them against existing measurements at Iskoras and Samoylov. Longer spin up runs will be used to reproduce observed carbon related state variables, such as soil carbon content. These simulations will provide the basis for investigating the response of carbon and methane pools and fluxes to climate change and estimating future GHG emissions. One advantage of the tiling approach is, that it allows to study the changes in carbon to methane ratio as inundate area and surface water height and extend change throughout the simulation and with that the carbon to methane ratio.

The new implementation has also been tested for global simulations and is intended to be upscaled to circumpolar uses. In this framework, grid cells meeting the environmental requirements for polygonal or palsamire landscapes will first be identified. Multiple two-tile structures representing the corresponding landscape types can be introduced within these grid cells. However, the geometrical parameters required by the approach are currently derived from high resolution, site specific studies and cannot be directly transferred to large-scale applications. For circumpolar upscaling, statistical approaches combined with existing field observations and remote-sensing products will be required to estimate representative geometric parameters across the permafrost region.