Simulating rapid permafrost degradation and erosion processes under a warming climate

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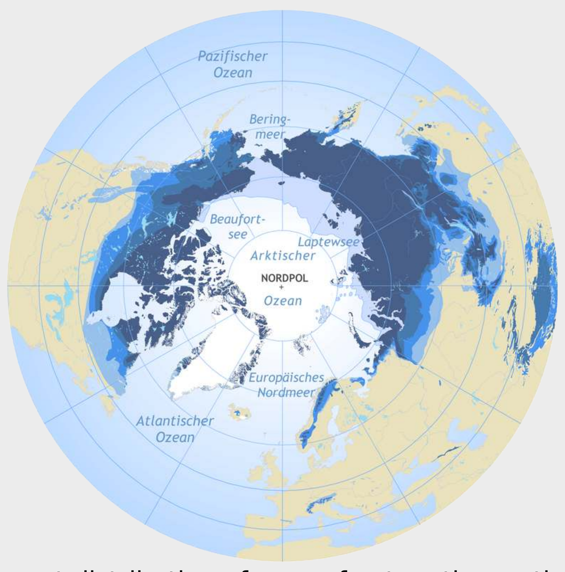
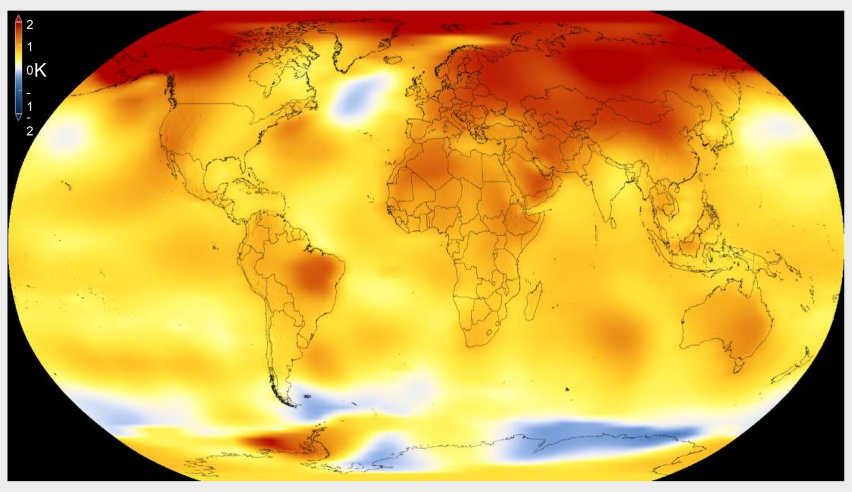
Background:

Permafrost under a warming Climate:



Current distribution of permafrost on the northern hemisphere.



Earth's surface temperature change between 1951 and 2017 (NASA: Scientific Visualization Studio)

Amplified climate warming in the Arctic leads to thawing of permafrost, triggering large-scale landscape and ecosystems changes and thereby severely impacting the heat, water, and matter cycles of Arctic ecosystems. The induced erosion and rapid thaw processes threaten the stability of Arctic ecosystems as well as infrastructure that is important to Arctic's life and economy.

In order to provide better predictions on the dynamics of Arctic permafrost landscapes we aim to develop a novel approach for simulating erosion and mass wasting processes based on a one dimensional land surface model.

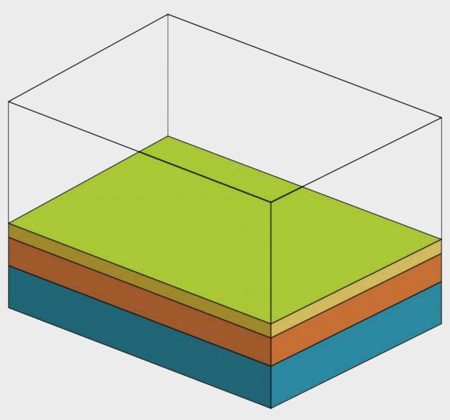
Here we present preliminary results of an modeling exercises to demonstrate capabilities of our model to simulate rapid thaw processes with an special focus on thaw slump dynamics.

Current State and Further Development of Land Surface Models:

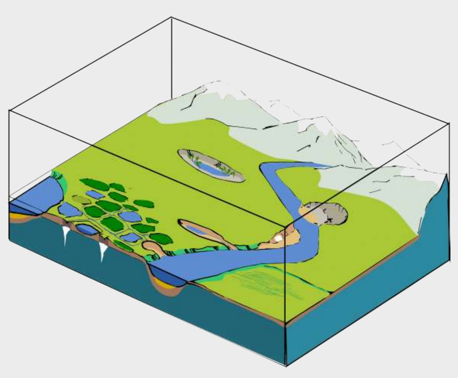
Photos: Josefine Lenz

Photographs showing typical features of permafrost degradation in the Arctic. Permafrost thaw is usually associated with intensive erosion and mass wasting.

Current Land Surface Models (LSMs) used to simulate the degradation of permafrost under a warming climate only consider one-dimensional (top-down) thawing and ignore lateral processes such as soil erosion and mass wasting which are the most abundant form of thaw in many regions.

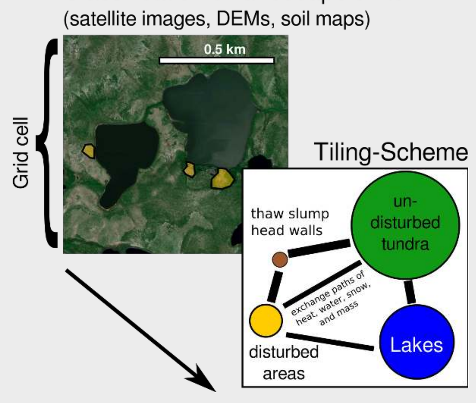


Schematic grid cell representation of a one dimensional LSM. With frozen and unfrozen soil layers



Envisioned representation of sub-grid landscape units and process within one grid cell.

Classification of landscape units
(satellite images, DEMs, soil maps)

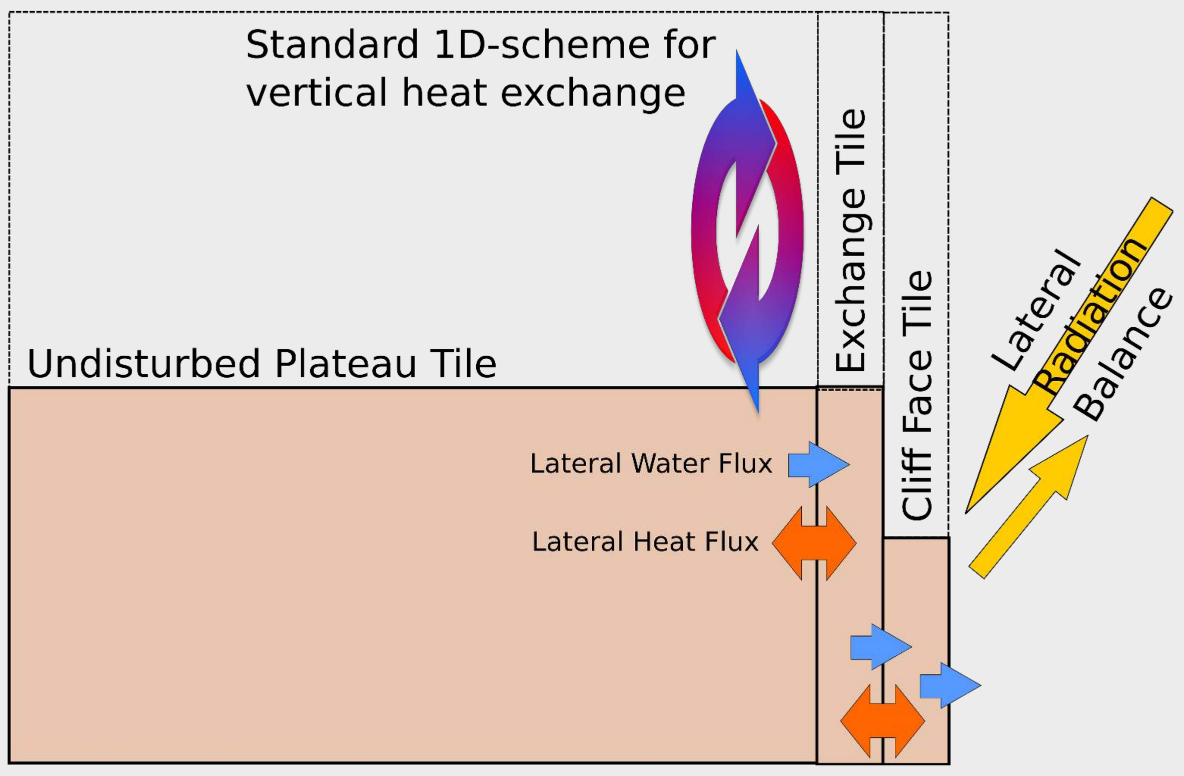


Conceptual illustration of the tiling scheme used to simulate thaw slumps and their interaction with surrounding landscape units.

The CryoGrid land surface model (Westermann et al., 2016) makes use of a tiling scheme that allows simulating processes on a sub-grid scale (e.g. Langer et al., 2016). The land surface is decomposed into virtual information allowing reduced order representation of processes that are much smaller than the nominal spatial resolution of the model.

Methods and Preliminary Results:

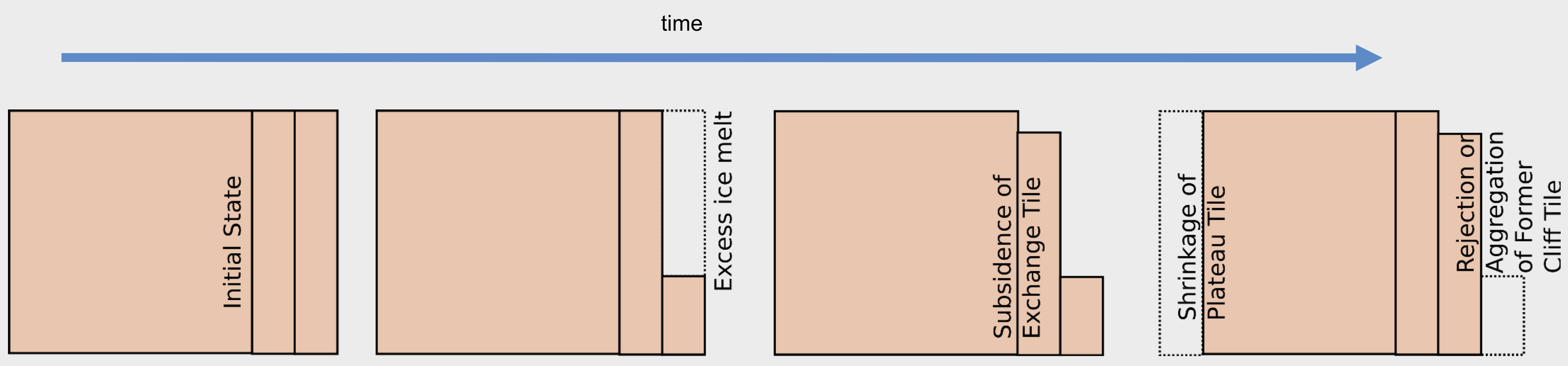
Model setup:



The model setup applied to represent a thaw slump by three tiles (relevant landscape units).

The landscape encompassed by one grid cell (typically representing 5 to 25 km²) is decomposed into landscape units that are relevant for investigated erosion processes

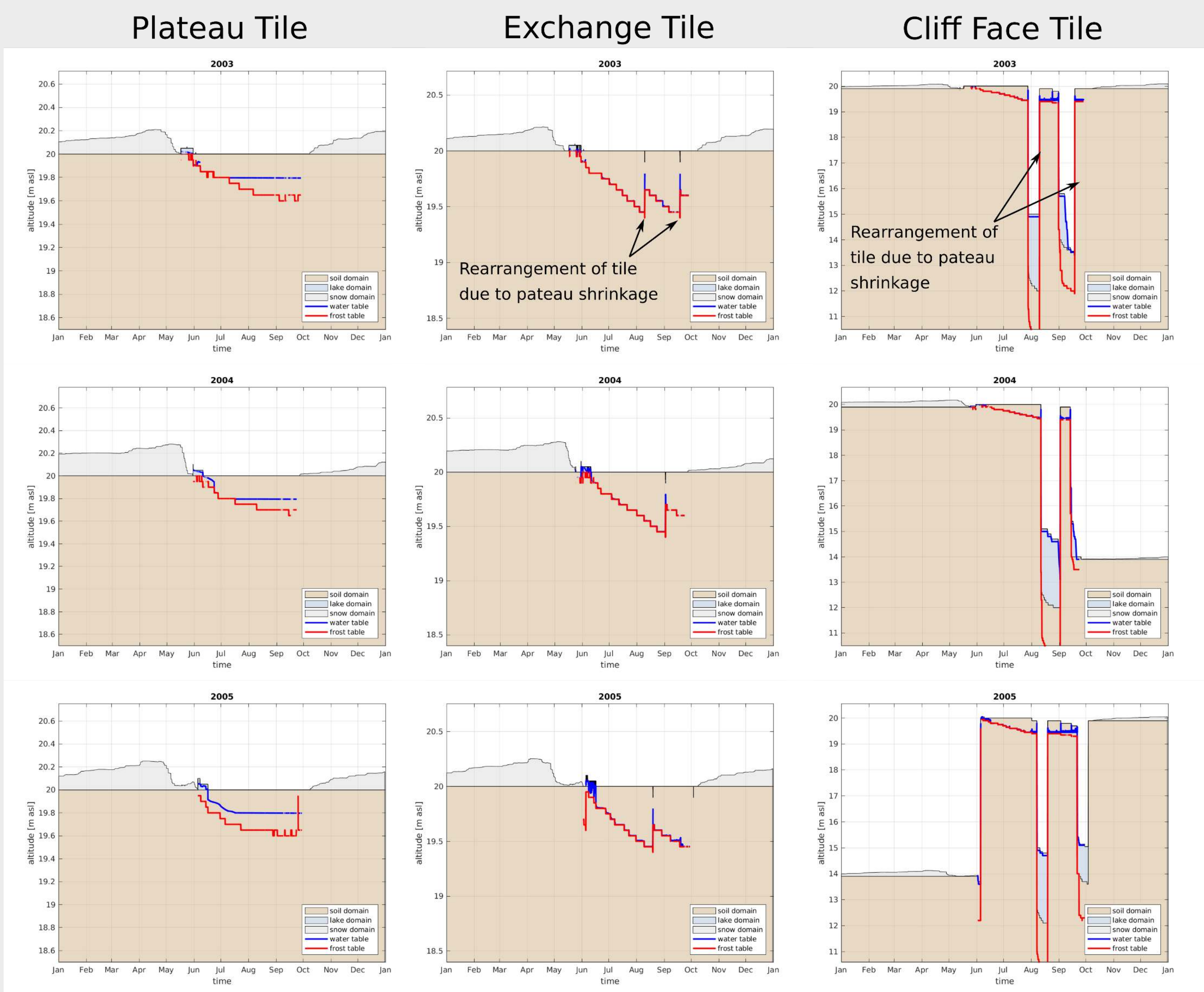
In the case of thaw slumps, we distinguish three relevant units such as the undisturbed plateau, an exchange tile, and the cliff face. Thereby, only the areal fraction and topological information such as hydrological connections, elevation differences, and distances determine the lateral exchange of water and heat, and the mobilization of matter.



Schematic representation of how the model simulates retreat of the heat wall due to the melting of excess ground ice.

Preliminary Results:

The highly simplified thaw slump scheme reproduces a head wall retreat between 0.2m to 0.6m per year between 2000 and 2014 for a site in Northwest Canada (Inuvik Region).
The magnitude of the heat wall retread strongly depends on exposition to solar radiation and the average summer air temperatures.
The model still lacks a realistic treatment of melt water runoff at the cliff edge. Furthermore, a physical meaning full parameterization that controls the rejection or aggregation of tiles at the cliff edge must be developed. Further model refinements also of the turbulent heat exchange at the cliff are necessary.
Nevertheless, the preliminary results demonstrate that a reduced order representation of thaw slumps is possible.



Simulation of a thaw slump represented by three interconnected tiles. The figures depict the annual dynamics of the active layer, the water level, the snow cover, and topographic hight. The discontinuities in the exchange and the cliff face tiles represent events of head wall retreat.

Relevant references:

Westermann et al., 2016: Simulating the thermal regime and thaw processes of ice-rich permafrost ground with the land-surface model CryoGrid 3, Geosci. Model Dev., 9(2), 523–546.

Langer et al., 2016: Rapid degradation of permafrost underneath waterbodies in tundra landscapes —Toward a representation of thermokarst in land surface models, J. Geophys. Res. Earth Surf., 121.

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