EGU25-15648, updated on 12 Jan 2026
https://doi.org/10.5194/egusphere-egu25-15648
EGU General Assembly 2025

Permafrost sensitivity to modified soil hydro-thermodynamics in MPI-ESM

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The intense warming of Arctic soils make them vulnerable to permafrost degradation, with critical implications for the global carbon cycle and regional ecosystems. However, the increasing temperature is not the only factor affecting permafrost degradation. Water availability changes in the Arctic considerably affect the soil moisture and ice presence and subsequently thermal structure in permafrost regions. The interaction between soil hydrology and thermodynamics is still poorly represented by most of the CMIP6 land surface models (LSMs), mainly in terms of the soil depth, vertical resolution, and coupling between hydrology and thermodynamics.

Using a modified version of the MPI Earth System Model (MPI-ESM), we investigate the sensitivity of permafrost to changes in soil hydrology and thermodynamics. Three different model configurations were tested to simulate varying hydrological states under future warming. Enhanced soil depth and vertical resolution within the land surface model, JSBACH, were also incorporated to capture fine-scale dynamics. The findings reveal that deepening JSBACH reduces the intensity of near-surface warming, reducing the deep permafrost degradation area by 3.1 million km^2 and constraining the active layer thickness deepening by the end of the 21st century under high-emission scenarios. However, hydrological configurations significantly influence model outcomes, with DRY and WET setups producing temperature offsets of up to 3°C and varying active layer thicknesses by 1–2 meters. The results highlight the crucial role of hydro-thermodynamic interactions in shaping permafrost dynamics.