# Permafrost-Cloud Feedback MIP

## General Hypothesis

Landscapes in the Arctic and subarctic zone are often very wet with water saturated soils and an extensive lake- and wetland cover shaping the moisture and energy exchange with the atmosphere. This, however, is likely to change in a warmer future. Here, the hypothesis is that a thawing of the ground predominantly leads to a lowering of the water table and an increase in hydrological connectivity. This causes a drying of the near-surface soil layers which, in turn, limits evapotranspiration and reduces the summertime cloud cover. The reduction in cloudiness increases the amount of radiation absorbed at the surface, thus, temperatures and thawing rates.

## Target of the investigation

In our recent investigation with the ICON Earth system model (de Vrese et al., 2024) we found that such a positive feedback indeed exists. Furthermore, our simulations suggest that the impacts on surface temperature are not limited to the Arctic and sub-arctic zone, but notably increase the global mean temperature. In case of our high-warming scenario by an additional 0.25°C. However, the overall response of the high-latitude hydrological cycle to rising temperatures is still dominated by factors other than changes in the soil hydrological parameters. This makes it extremely difficult – if not impossible -- to isolate the respective effects in the output of existing simulations. Thus, an assessment of the global-scale impact of the permafrost cloud feedback requires simulations that directly target the effects due to changes in hydrologic connectivity.

## General setup

The general aim is to investigate a future scenario under elevated GHG concentrations and to compare fully coupled ESM simulations in which (i) permafrost thaw does not result in an increase in hydrological connectivity (NoDrain) to coupled ESM simulations in which (ii) the degradation of soil ice facilitates drainage and the drying of the near-surface soil layers (REF). While REF should be performed with the standard configuration of your model, the idea for the NoDrain simulation is to identify those soil hydrological processes that are affected by the presence of permafrost and “fix” these within a predefined region, the initial permafrost domain (IPD; Figure 1). Thus, runoff and drainage within the region behave as if permafrost was present in the grid cell even after the latter is degraded under

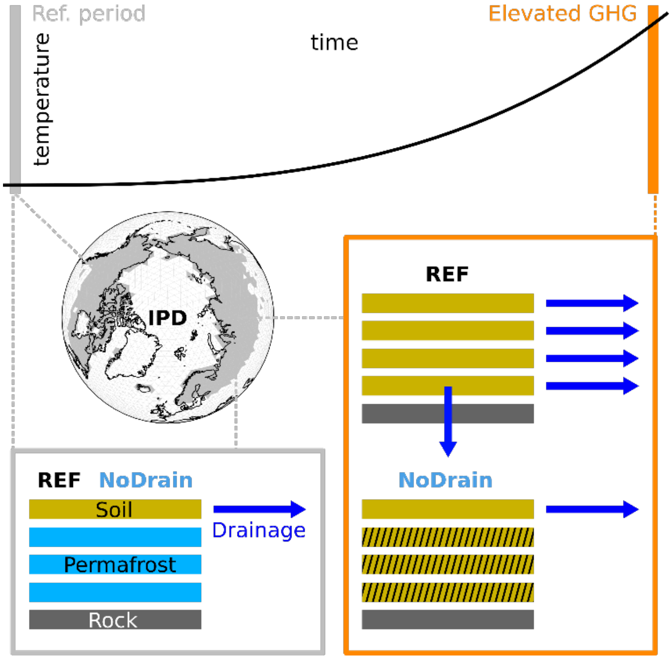


*Figure 1: Sketch outlining the general idea of the simulations, with the reference and target periods (Elevated GHG) shown at the top. The initial permafrost domain (IPD), as simulated with the ICON model for pre-industrial conditions, is shown at the center left. The grey box at the bottom left shows the drainage from permafrost affected soils. The orange box at the bottom right indicates the different treatement of the drainage fluxes by the REF simulation and the NoDrain simulation after the permafrost is degraded within the initial permafrost domain.*

elevated GHG concentrations. Here, the IPD is defined as the region in which the soil hydrological processes are affected by permafrost during a reference period, e.g. the pre-industrial period.

## Modification of the model

Most models employ ice-impedance factors to determine the hydrological fluxes below the surface including subsurface runoff. In this case, the NoDrain simulation requires limiting the ice-impedance factors to the values that were simulated during the reference period in those regions and soil layers that remained permanently frozen during the reference period. In practical terms, these models would have to be adapted to allow reading in a field of annual maximum ice-impedance factors and then use the minimum of these values and the values simulated during runtime to determine the drainage rates. Here, it should also be possible to prescribe zero-values in the IPD instead of values from a reference period (which may make things easier as these factors are most likely not included in the output of existing simulations). Finally, it may be necessary to introduce specific impedance factors for drainage and for the vertical movement within the soil. These may be needed since an inhibition of percolation into the formerly frozen layers may lead to complications with respect to the plant water uptake and stress, and -- if these layers dry -- also with respect to the energy transport within the soil.

In models that do not use such factors, an additional condition needs to be introduced that allows switching of the calculation of the drainage fluxes in specific grid cells and soil layers, with the respective mask being an input field for the model. In the worst case, when permafrost has no effect on the hydrological fluxes (such as the standard setup of MPIESM [ICON's predecessor] where water does not freeze), the NoDrain simulation cannot be meaningfully compared to REF runs with the standard model. Here, an inhibition of the drainage fluxes in the presence of permafrost also needs to be implemented for the reference simulations, which may be as simple as not permitting any drainage from soil layers with sub-zero temperatures.

Another general modification pertains to those models that move excess water from each soil layer to the discharge individually. Here, the code would have to be changed (at least for the grid cells within the IPD) so that the excess water from one soil layer is passed to the layer above rather than draining from the soil directly. If such a modification is required, the reference simulation also needs to be repeated with the same assumption of excess water "piling up" in the soil.

Of course, we would be more than happy to help as best we can with the required model adaptation.

## Required simulations

At a minimum, the intercomparison would require a single simulation under elevated GHG concentrations using a modified model. This NoDrain simulation, in which runoff and drainage are artificially inhibited within the IPD, could then be compared to an existing model run (REF), with the standard model configuration and the same atmospheric GHG concentrations (Figure 2**Error! Reference source not found.**). Additional simulations may be required to determine the IPD and those factors inhibiting the hydrological fluxes within the region (but this could possibly also be done based on the soil temperatures in existing simulations), if the reference run also requires a modification of the permafrost hydrology, or if we chose to investigate a scenario(s) for which no reference run exists.

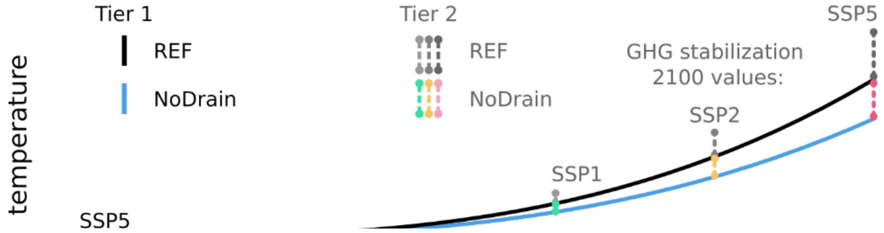
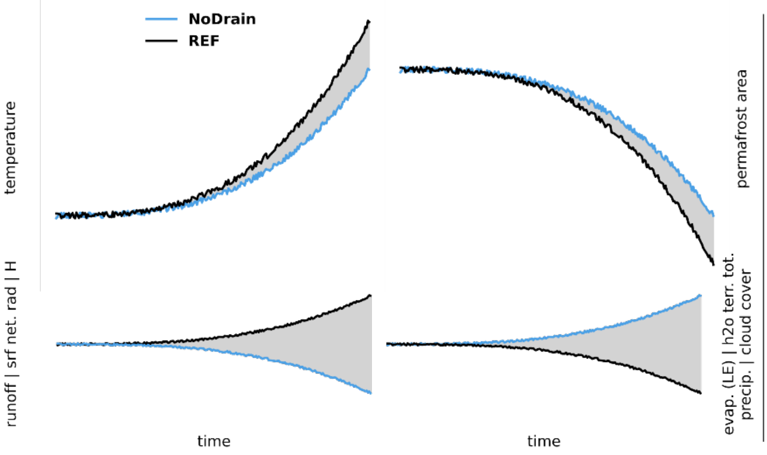


*Figure 2: Overview over possible simulations*

Here, high-warming scenarios such as SSP5-8.5 would be the most informative case -- since the magnitude of the feedback effects depends on the fraction of the permafrost area that has been lost (relative to the reference period) -- even though these may not necessarily be the most plausible GHG trajectories. However, if computational resources are not a (strongly) limiting factor, it would be great to investigate the feedback effects for a number of GHG scenarios. Given the large inertia of the permafrost system, it may make sense to perform these additional simulations assuming stable GHG concentrations, possible looking at end-of-the-21st-century values of SSP1, SSP2 and SSP5 or at those GHG concentrations that correspond to certain temperature levels in the reference run, i.e. 2°C, 3°C and 4°C above pre-industrial levels (though there will most certainly be a drifts in the temperatures under stable GHG concentrations).

## Required output

The intercomparison does not rely on any special output and the variables needed should all be part of what is asked for by CMIP. Here, the minimum requirements (Figure 3) are global fields of surface and soil temperatures (the latter to estimate the permafrost extent), precipitation, runoff and drainage, evapotranspiration, total terrestrial water storage, cloud cover and all the components of the surface energy balance (radiative fluxes possibly also for clear sky conditions to estimate the cloud radiative effects).



| Long name | units | CMOR |
|---|---|---|
| Downward Heat Flux at Land Surface | W m-2 | hfdsl |
| Evaporation | kg m-2 s-1 | evspsbl |
| Percentage Cloud Cover | % | cl |
| Precipitation | kg m-2 s-1 | pr |
| Relative Humidity | % | hur |
| Surface Downwelling Clear-Sky Longwave | W m-2 | rldscs |
| Surface Downwelling Clear-Sky Shortwave | W m-2 | rsdscs |
| Surface Downwelling Longwave | W m-2 | rlds |
| Surface Downwelling Shortwave | W m-2 | rsds |
| Surface Temperature | K | ts |
| Surface Upward Latent Heat Flux | W m-2 | hfls |
| Surface Upward Sensible Heat Flux | W m-2 | hfss |
| Surface Upwelling Longwave | W m-2 | rlus |
| Surface Upwelling Shortwave | W m-2 | rsus |
| Temperature of Soil | K | tsl |
| Terrestrial Water Storage | kg m-2 | mrtws |
| Total Cloud Cover Percentage | % | clt |
| Total Run-off | kg m-2 s-1 | mrro |

*Figure 3: Overview over minimum output requirements*

While these are the minimum requirements, it would be extremely helpful for an investigation of the global-scale impacts if sufficient output was provided to be able to connect any remote impacts to the causative effects in the high latitudes. This would include, but not be limited to, the TOA energy fluxes, sea ice extent and thickness, atmospheric temperatures, wind fields, ocean temperatures and velocity fields, ocean heat transport / uptake / storage and MOC strength.

## Initial Study

de Vrese, P., Stacke, T., Gayler, V., & Brovkin, V. (2024). Permafrost cloud feedback may amplify climate change. Geophysical Research Letters, 51, e2024GL109034. https://doi.org/10.1029/2024GL109034