Project:	**1236**
Project title:	**Q-ARCTIC**
Principal investigator:	**Victor Brovkin**
Report period:	**2024-11-01 to 2025-10-31**

Shrub representation in ICON-LAND/QUINCY

To improve vegetation representation, we added two shrub plant functional types (needle-leaved evergreen and broadleaved deciduous) to ICON-LAND/QUINCY and applied the scheme globally for the first time. The detailed plant phenology coupled to soil biogeochemistry and hydrology represented by QUINCY allows us to simulate dynamic vegetation phenology in Arctic conditions. By implementing needle-leaved evergreen and broadleaved deciduous, the two most common shrub types in the Arctic, we now prescribe 9 % of the Arctic land coverage with shrubs (7 % globally) based on the most recent developments of cross-walking tables (DOI: 10.5194/essd-15-1465-2023), ESA-CCI landcover data and a new parameter set up. The simulation shows are reasonable spatial distribution of biomass with 0.5-2 kgC m-2 in the Arctic as found in the literature. Shrubs produce 27 % (BD shrub, brown line) and 56 % (NE shrub, gray line) of the biomass production by the old BD PFT (green line). The growth of the new BD PFT is almost the same as of the old PFT. Much more carbon, however, is stored by shrubs below ground (BD shrub: 65%, NE shrub: 118%, not shown) compared to trees as indicated by other studies.

Intra-Tile lateral flow representation

We previously extended the tiling-infrastructure employed in ICON-Land to be able to represent individual classes of surface clusters (the tiles) based on topographic features, the so called HydroTiles. This infrastructure has been generalized making it possible to subdivide the land surface within a grid cell based on any surface or sub-surface property. This scheme, called T-REX (short for “tile-based representation of lateral exchange processes in ICON-Land”), does not only facilitate the classification of the subgrid-scale clusters by allowing to read in tile-specific boundary data, but it also makes it very simple to define the connections between the tiles, which govern the lateral exchange fluxes. The scheme allows representing the horizontal fluxes on a broad range of spatial scales and includes 5 lateral exchange processes, namely gravity-driven moisture fluxes and the corresponding convective heat transport, diffusive- and conductive fluxes of water and heat as well as the wind-driven redistribution of snow. The detailed description of this model development has recently been submitted to GMD.

Finally, we had also planned to implement further permafrost-related processes such as subsidence and thermokarst lake dynamics. In two PhD theses we, therefore, explored the feasibility to implement the dynamics using stochastic approaches. Unfortunately, both investigations demonstrated that the limitations of observational data make it impossible to derive the required statistical parameters at this time.

ICON-Land permafrost carbon representation

ICON-Land originally contained a carbon cycle representation inherited from the JSBACH model implemented in MPI-ESM. While this carbon cycle representation fulfilled many of the requirements for faithfully representing carbon cycle dynamics in the permafrost region, it was lacking in one major respect: The YASSO soil carbon model contained in JSACH3 is a zero-dimensional representation of soil carbon dynamics lacking a consideration of depth.

The original planning in Q-Arctic had been to instead employ the more modern carbon cycle representation QUINCY, as it is superior in many respects. QUINCY development is, however, not yet advanced far enough and still lacking a representation of dynamical changes in vegetation cover — highly important for representing large future climate changes.

We therefore developed the YASSO soil carbon model further by implementing a vertical dimension to the carbon storage, allowing a representation of frozen carbon stored in deeper soil layers. This model development is by now finished.

Large Eddy Simulations with the EULAG model

Surface atmospheric exchanges during stratified conditions are least explored due to uncertainties associated with the application of traditional flux measurement techniques like eddy covariance. Given the importance of stable stratification in the Arctic atmosphere, it is essential to investigate its dynamics in greater detail. We simulated the stable boundary layer using high resolution LES. However, under strongly stable conditions, a significant portion of eddy diffusion is represented through sub-grid scale parameterizations, limiting our ability to understand the influence of weak turbulence. To address this limitation, we employed Implicit LES (ILES) at very high resolution (0.01 m) using the EULAG model. These high-resolution experiments using LES and ILES required more node hours than initially anticipated.

Furthermore, EULAG was utilized to study the Permafrost Cloud Feedback (de Vrese et al., 2024) in a feasibility study. We used the model to simulate cloud formation and rain development explicitly on the resolved scales in order find the link between surface characteristics in terms of water content, or moisture in general, and the backscatter of incoming solar radiation (albedo) of the consequential cloud cover. Preliminary results were very promising and presented with a talk at the AGU24 General Meeting. These results were based on low-resolution runs which saved node-hours but need to be confirmed with more costly high-resolution simulations.

In another study, EULAG was employed to infer surface fluxes of green house gases from Unmanned Aerial Vehicle (UAV) based greenhouse gas concentration measurements. The inversion fluxes were subsequently compared to patch-level chamber measurements of carbon dioxide and showed a good agreement in flux patterns across those patch types dominating the UAV-sampled footprint. Since the inversion relied on an optimization method, many individual model runs of EULAG were necessary as a means to achieve this goal. The results of this effort were published in Yazbeck et al. (2025).

Permafrost cloud feedback in ESM simulations

The permafrost cloud feedback was first studied using ICON-ESM v1.0. Here we were able to qualitatively confirm our initial findings with simulations with the ICON SEAMLESS / XPP setup. However, the results differed substantially with respect to the magnitude of the impact on the global mean temperature. This suggests that a robust assessment of the feedback strength requires simulations with a number of different ESMs. Here, we initiated the permafrost-cloud-feedback MIP (https://q-arctic.net/activities) and we helped to implement the required code modifications in particular for AWI-ESM (JSBACH3), CESM2 (CLM) and NorESM (CLM). The MIP is an ongoing effort and we expect to be able to analyze the simulations sometime during the first half of 2026.