Project:	**1236**
Project title:	**Q-ARCTIC**
Principal investigator:	**Victor Brovkin**
Report period:	**2023-11-01 to 2024-10-31**

Summary

This years achievements comprise the demonstration of a permafrost-cloud feedback in ICON, simulations using the terrestrial ecosystem model Quincy in combination with ICON-LAND, and the application of the LES Model EULAG for the simulation of surface heterogeneity effects on land atmosphere interactions. Furthermore, a number of bugs were discovered that severely affected the simulation of land surface processes and bugfixes were implemented to deal with these issues. Most of these bugs were not anticipated before and caused a delay in our simulation plan shifting our more expensive, coupled simulations towards the later part of the year. Also the EULAG simulations experienced unexpected delays due to later than anticipated personal hires in the Q-Arctic project. Therefore, less node hours than applied for were used.

Permafrost cloud feedback

Using the surface-tilling that was developed in the Q-Arctic project to describe soil-hydrological sub-grid scale heterogeneity in ICON, we could demonstrate that thaw-induced shifts in the state of Arctic and sub-arctic soils have a large potential to amplify local and regional temperature changes, via a positive feedback with the low-altitude cloud cover.The thawing of the ground increases its hydraulic connectivity and raises drainage rates which facilitates a drying of the landscapes. This limits evapotranspiration and cloud formation during the snow-free season. A decrease in summertime cloudiness, in turn, increases the shortwave radiation reaching the surface, hence, temperatures and advances the permafrost degradation. Our simulations further suggest that the consequences of a permafrost cloud feedback may not be limited to the regional scale. For a near-complete loss of the high-latitude permafrost, they show significant temperature impacts on all continents and northern-hemisphere ocean basins that raise the global mean temperature by 0.2 5 K (Fig. 1). The respective results were published in an article in Geophysical Research Letters (de Vrese et al., 2024)

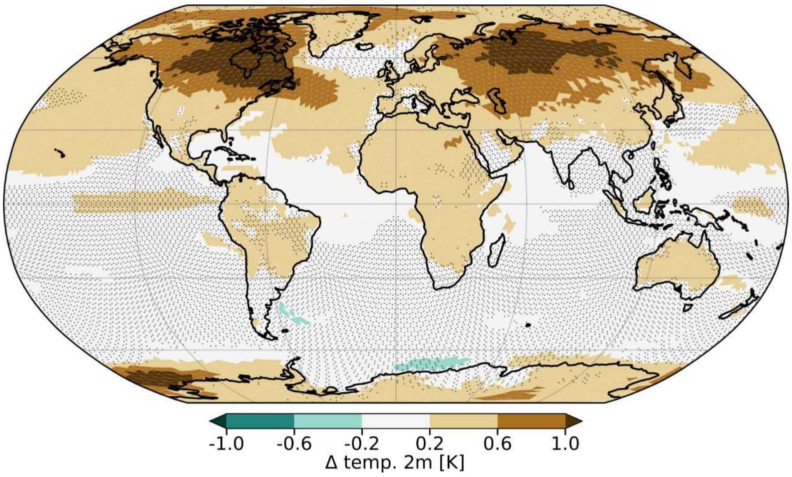

Figure 1: Additional warming due to the drying of high latitude landscapes as a result of permafrost thaw. The impact was estimated based on fully coupled ICON simulations, targeting the end-of-the-century greenhouse gas concentrations of SSP5-8.5.

Modelling of soil carbon with QUINCY

This project has been started in Mai 2024 and aims at evaluating and projecting soil carbon in the Arctic. Therefore, it fits within the framework of Q-Arctic, however, it was not part of the last request. In the project, the biogeochemistry model QUINCY, developed at MPI Jena, is firstly employed in Hamburg. As most important advances, QUINCY includes interactive cycles of carbon, nitrogen and phosphorus driving the vegetation. Also, the soil processes are explicitly resolved in the vertical. First, a QUINCY offline simulation was set-up with an unlimited nitrogen supply. Two set-up specific settings were tested in 20-yr simulations before employing the model for 520 years (400 yr spin up). The first result for soil carbon (0-1m) shows a reasonable global distribution (Fig. 4). However, soil

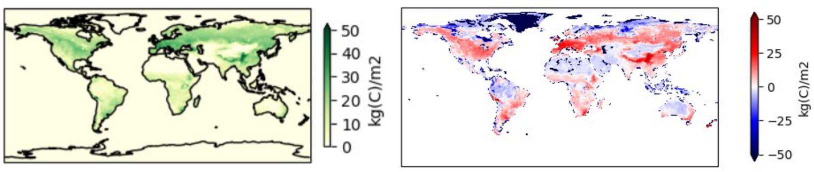

Figure 2: Global distribution of soil carbon in top 1m (left) and absolute difference to the Harmonized World Soil Database (HWSD) v1.2 dataset (sim-obs, right).

carbon in the Arctic is significantly underestimated because peatlands are not yet represented. The overestimation in Europe can be probably explained by too high carbon sequestration in this region.

Coupling the Carbon and Hydrological cycles: HydroCarb

In HydroCarb we performed numerous test experiments to assess whether model components perform as expected, and whether required model components interfere with each other. These covered mainly the terrestrial hydrological and carbon cycles and extended over time frames of years to centuries and identified - and fixed - several model errors.

Large Eddy Simulations with the EULAG model

Arctic permafrost thaw could significantly change the Earth's surface in northern regions. We used the EULAG research model to study how these changes affect the atmospheric boundary layer, focusing on landscapes with grass and water, which have different surface haracteristics. We found that the amount of lake area influences the heat flux, with more lakes leading to less heat flux, potentially speeding up permafrost thaw as the Arctic dries. Additionally, the height at which surface features are blended in the atmosphere depends on the surface's correlation length, a factor often overlooked in current models. The EULAG model was run on the Levante cluster and the results were published in Schlutow et al. (2024). Complex flow fields as model output, which were analyzed to prove our hypotheses, are shown in Figure 3.

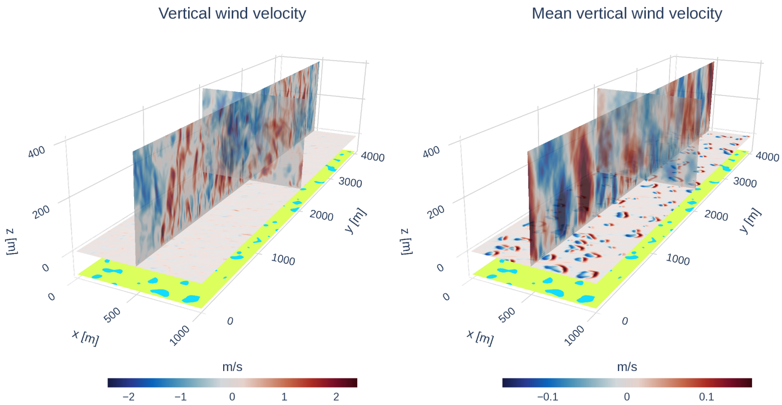

Figure 4: Large Eddy Simulation results. The flow field over a stocastic permafrost lake landscape is shown.

A great deal of development went into the inclusion of water vapor, condensed water particles and rain water into the EULAG model. Furthermore, EULAG was used to generate synthetic data in order to simulate what an autonomous Unmanned Aerial Vehicle (UAV) equipped with trace gas sensors would measure. Real UAV trajectories were implemented in the model domain to simulate flights. The actual gas sensors were configured by means of the synthetic data in preparation to a field campaign that took place in the Canadian Arctic in 2024. In a third project, EULAG was used as a tool for trace gas flux inversion. Based on concentration fields observed by our UAV in the Swedish Arctic, the goal is to infer the ground sources of the trace gases. We were able to reconstruct the source distribution by the implied concentration fields. We used much less node hours than initially anticipated in this project as the inversion expert was hired only by June 2024 which was more than half way through the application period.

Bugfixes and process improvements in ICON-LAND

A bug was found related to the computation of soil temperatures. In a recent land surfaced evaluation, snow and soil temperatures where found to be too cold during boreal winter. This behavior is caused by an inconsistency during the computation of snow and soil temperatures for areas that are partially snow covered and - effectively - allows too much of the heat trapped below the snow to escape via the snow-free surface of the grid cell. A bugfix was developed to work around this problem by assuming existing snow always covers the full grid cell, which strongly improves the simulated soil temperature. Furthermore, we did extensive changes to the soil hydrology. We introduced a new soil property, the residual water content, as lower limit for vertical water transport within the soil column and replaced the soil field capacity with porosity as upper limit for maximum soil water content, wherever this was still used in the soil physics.This makes ICON-LAND more consistent with the standard hydrological understanding. Additionally, infrastructure was implemented to choose between a semi-distributed hydrology parametrization that accounts for sub-grid variability in infiltration and subsurface drainage to be used for coarse scale simulations, and an alternative parametrization that assumes a uniform distribution of soil moisture. The latter is required for high resolution, site-level or HydroTiles applications as planned within Q-Arctic. Overall, the changes have only small impacts compared to the reference model, but they adhere to a more consistent representation of soil physics and thereby facilitate the development of Q-Arctic specific processes.