DKRZ resources request 2020 for project 1026: ILModels/GReatModelS – 2019 report

Project Title:
Global and Regional Impacts of using more realistic Land Modelling on Historical and Climate Change scenario Simulations (GReatModelS)

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Background

GReatModels is the follow-up project of ILModelS (1026). In ILModelS, we tested the effects of improved subsurface representation in the standalone version of JSBACH (Hagemann et al., 2013), the atmosphere model ECHAM6.3 (including JSBACH), and the Max-Planck-Institute Earth System Model (MPI-ESM, including JSBACH and ECHAM6, Giorgetta et al., 2013; Jungclaus et al., 2013). There is a number of evidences (MacDougall et al. 2008; González-Rouco et al. 2009) suggesting that the simulations of subsurface thermodynamics in current GCMs might not be accurate enough since typically the thermodynamic component in a LSM makes use of an insufficient number of discretized subsurface layers and imposes a zero heat flux Bottom Boundary Condition Placement (BBCP) that is located too close to the surface. Most of the current generation of GCMs use BBCPs that are shallower than 10m depth.

Status after ILModelS and scope of planned work

Phase 1:

ILModelS' results have shown a considerable impact of increasing the depth of the soil model on the subsurface thermal regime (González-Rouco et al., in prep.). In the first project phase, we extensively used the standalone JSBACH version to derive results for different radiative forcing simulations (piControl, PIC; historical, HIS; and scenario, RCP) with the modifications developed in the project. We have explored the effects of increasing the depth within the LSM in off-line control, historical and scenario simulations that have proved an impact in the ground and surface temperatures due to the extra space allowed to store energy and also water in the subsurface. Conductive propagation of the rcp8.5 scenario surface temperature signal of ~+7K (compared to piC conditions) into the ground in the deep model (Fig. 1) shows the subsurface to be affected to a depth of at least 274m.

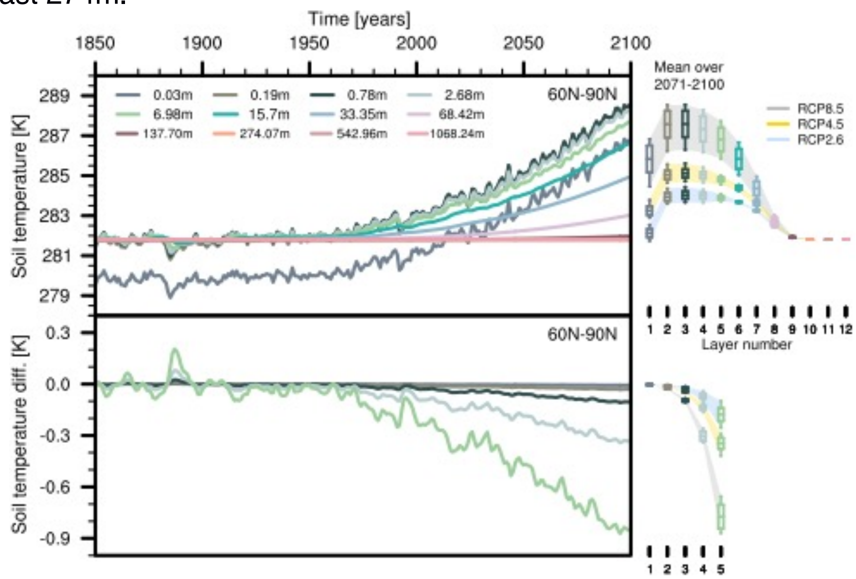

Fig. 1: Global absolute subsurface temperature in the 12-layer deep BBCP configuration (top) and global subsurface temperature difference between the 12-layer deep and 5-layer shallow BBCP configuration (bottom) for the combined historical (1850-2005) and RCP8.5 (2006-2100) simulations.

It is evident that the standard shallow JSBACH with a depth of 10m compromises the representation of the ground thermal state. The comparison between the deep and shallow model gives a warm bias in the shallow (near-surface cooling in the deep) model of almost 1K in the global mean. This cooling is intensified in the northern high latitudes independent of the strength of the forcing scenario. Although there is a surface cooling with a deeper soil model, the terrestrial annual mean heat content change is positive. Both effects can be explained by the space made available by increasing the vertical depth of the soil that allows the temperature signal to penetrate deeper into the soil attenuating homogenously with depth, which matches well the expectations (e.g. Smerdon and Stieglitz., 2006; MacDougall et al., 2008; González-Rouco et al., 2009). The heat residing near the surface in the shallow model is released to deeper layers when physical space is available (Fig. 2). With a BBCP-depth below 300m, the soil gets saturated for the time-scales considered. However, even when the land surface model component has an insufficiently deep BBCP, improvements of increasing the BBCP-depth by just a bit, are largest. A paper on this development with respect to the thermodynamic aspects is currently in preparation and it is expected to be submitted in 2020 (González-Rouco et al., in prep.; González-Rouco et al., 2017a; 2017b; 2017c; 2018; Steinert et al., 2018a; 2018b).

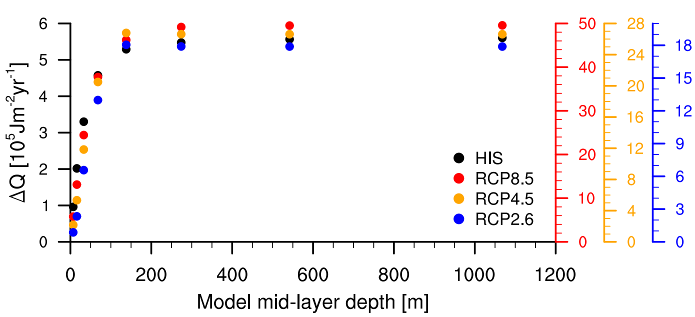

Fig. 2: Global mean annual terrestrial heat content change ($10^5 Jm^{-2}yr^{-1}$) in dependence to the BBCP-depth configuration.

Phase 2:

In the project phase two, we introduced (Steinert et al., in prep.) different soil hydrological states, with major implications for vertical soil moisture distribution and its exchange with the land surface under the condition of a deeper soil. Specific efforts addressed the inclusion of permafrost-related processes in comparison to the standard model. This allowed for sensitivity experiments considering water phase changes that have been conducted with implications for climate variability and change at the regional level in areas where freezing and thawing are of importance. In the development of JSBACH, an option for permafrost-optimized soil (POS) was introduced (*Ekici et al., 2014*), which supports more realistic water states and movements in high latitudes. The standard POS allows for phase changes (LHE; which the standard JSB does not have), a dynamic calculation of the heat conductivity (DCC) and a modified 5-layer snow module (SNOW). It omits the presence of supercool water (SCW). Hydrological sensitivity is tested by the implementation of two different soil parameter datasets (SPDs). We focus on the northern high-latitude permafrost areas, which capture a considerable amount of carbon and are vulnerable to climate change.

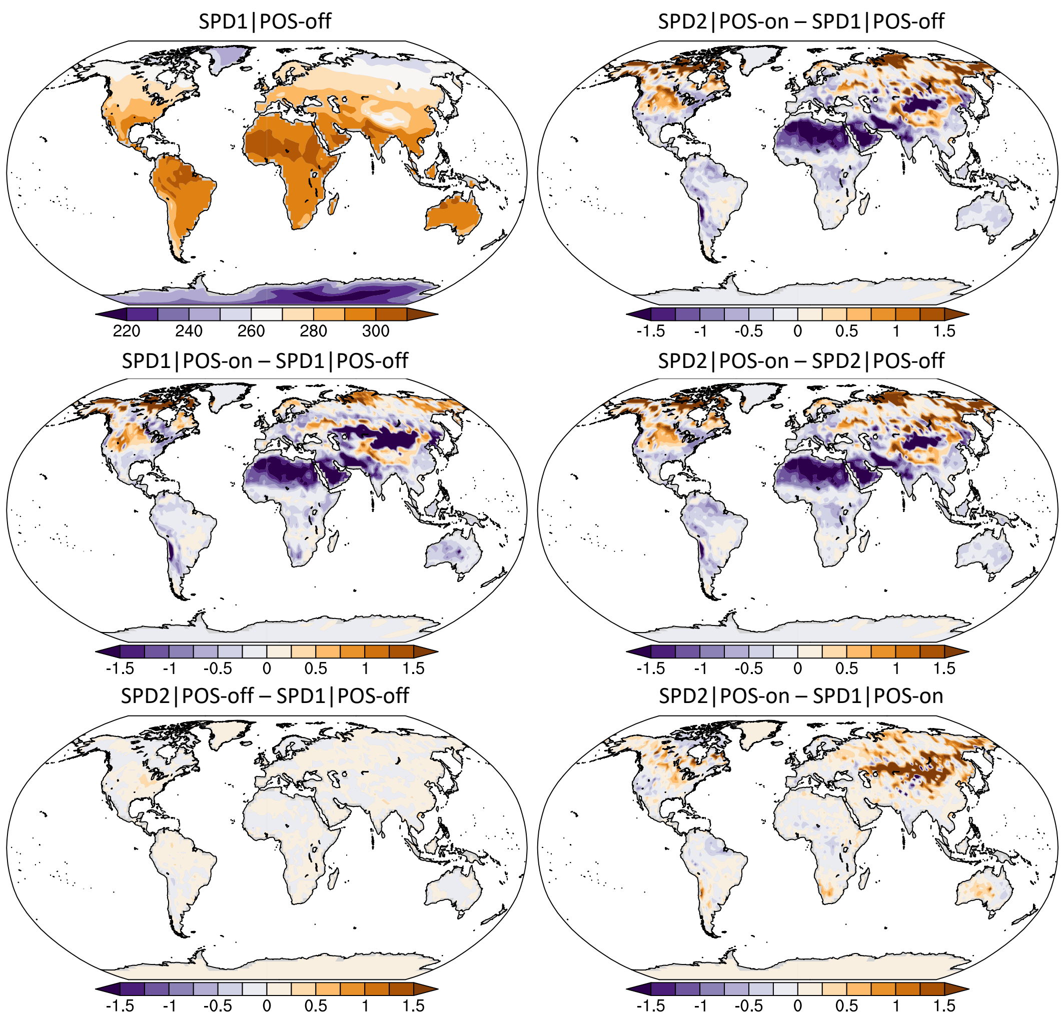

Fig. 3: Absolute (top left) and difference (rest) temperature [K] at model layer 5 (6.98m) in the deep model for different soil hydrological conditions of POS and SPD in piC conditions.

Alteration of the hydrological state and thermo- hydrodynamical processes (POS-off/POS-on) reveals multiple responses in the deep model (Fig. 3). A change in SPD-related variables has almost no influence under POS-off, but considerable warming in the northern mid-to-high latitudes with POS-on. The model with permafrost-optimized soil shows particular pattern with massive cooling in desert areas and warming in high-latitude regions for both SPD1 and SPD2. The pattern can be explained by the contribution of different physical mechanisms taking part in POS-on (Fig. 4). Particular impact comes from the contribution of changes in the snow scheme that triggers the thermo-insulating effect of snow cover and the introduction of latent heat exchange due to water phase changes. A superposition of the single pattern in Figure 4 may not explain the final response POS-on in Figure 3 because feedbacks and intertwining processes occur. Depending on regions and hydrological conditions, 7-17 times more heat is stored in the deep model (not shown). The northern high latitudes capture the surface warming of the 21st century the most. Apart from the regions north of 60N, altering thermo-hydrological processes has only little influence in the ground heat storage. However, in hydrologically active regions, changing the soil parameter dataset has a significant effect. In some regions, the difference of energy storage between the two SPDs accounts for as much heat as is stored in the shallow model alone. Interestingly, a deeper soil model shows a relatively stronger response in the moderate rcp4.5 than in the stronger rcp8.5 scenario. A paper with the focus on the sensitivity and evolution of the terrestrial thermal and hydrological state in the present and future climate, is currently in preparation and it is expected to be submitted in 2020 (Steinert et al., in prep.).

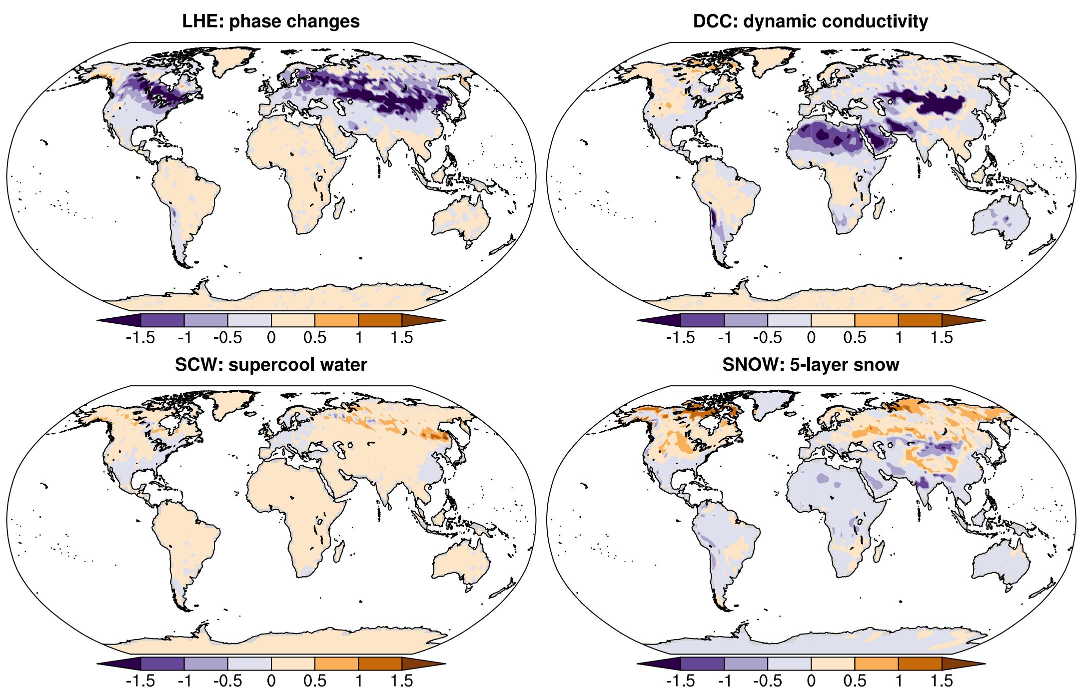

Fig 4: Soil temperature differences [K] between different model configuration that allow or omit specific soil thermo-hydrological processes, which allows to extract their individual contribution to the full POS-on signal in Figure 3.

The evolution of permafrost extent in the rcp8.5 scenario is driven down sharply by the warming by 2100 (Fig. 5). Differences of up to 80% are visible between the two SPDs. Compared to that, the soil-depth variation has little, but still significant, influence in the permafrost evolution. This underlines the large uncertainty that is still present in state-of-the-art Earth System Models. Despite the large differences in our results, we cannot argue that one state is more realistic than another, but rather pointing out the sensitivity of Land Surface Models to varying soil conditions.

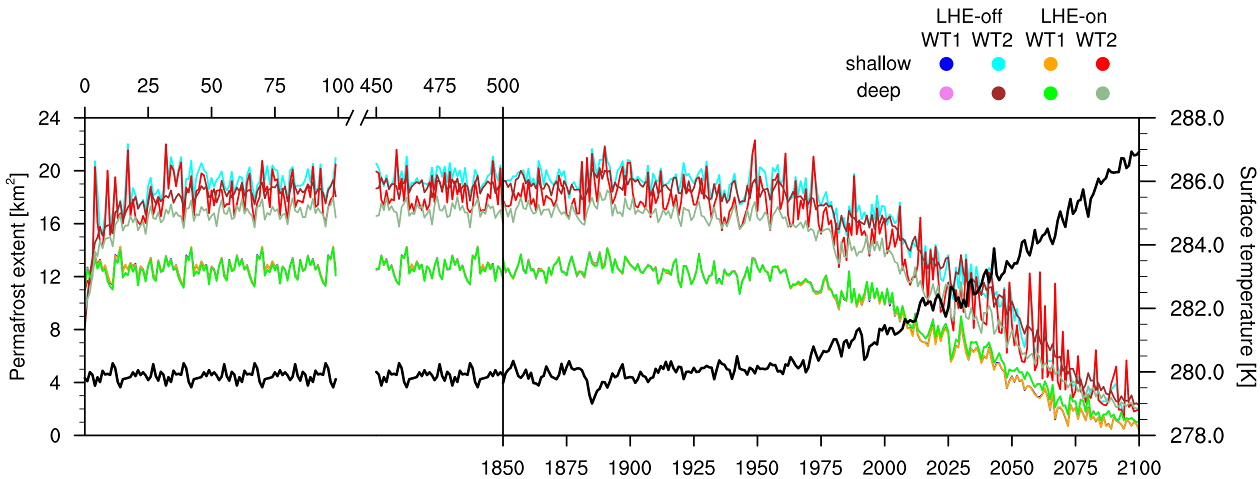

Fig 5: Permafrost extent ($10^6 km^2$; 45-90N) in different soil hydrological conditions of POS and SPD (colors) and surface temperature (K; black) from pre-industrial to rcp8.5 forcing conditions.

ECHAM6 simulations

In addition, we have launched the atmosphere-coupled version ECHAM6 for PIC, HIS and RCP radiative forcing conditions to prepare the next project phase. This allows for a more realistic representation of energy balance at the surface and terrestrial energy storage that is not possible in the JSBACH standalone experiment. We understand that running the atmosphere-coupled simulations occupies far more computational time and storage than the stand-alone version. For this reason, we limited our simulations to the choice of the shallowest and deepest model configurations only. The adaptation of the model to improved hydrological representation in terms of the permafrost-optimized soil shows problems in climate stability in ECHAM6, so the standard version of JSBACH permafrost representation was used. As for JSBACH standalone, the newly developed initial condition soil parameter datasets were implemented as well. Following that, sensitivity tests need to be performed next in order to understand the contribution of the implementation of cold-region hydrological processes, similar as in JSBACH-standalone. The analysis of this set of simulations will allow a more comprehensive evaluation on the impacts of allocating more space for energy- and water-related processes when the LSM is coupled to the atmosphere in a more realistic climate.

Fully coupled MPI-ESM simulations

The improvements will finally be tested in the coupled system MPI-ESM to allow for a global scale evaluation of impacts on the energy balance. In such a way, we will be able to evaluate the net effect of each one of the principal climate sub-systems on the climate variability simulated using a deeper and more realistic soil module. Such analysis grants the feedback with the simulated climate subsystems in fully coupled experiments.

Additionally, to investigate the effect of the LSM depth on long-term climate variability in a GCM, a Last2k simulation shall be carried out with the MPI-ESM in the frame of GReatModelS. This will include agreed PMIP4 forcings (Jungclaus et al. 2016) and will allow for contributions to the next generation of PMIP4 runs with an MPI-ESM that incorporates a more realistic soil model (e.g. Melo-Aguilar et al., 2017, 2018b, 2018c, 2019). Therefore, the aim is to provide last millennium simulations based on the MPI-ESM with an improved version of the land component in the context of the CMIP6/PMIP4 community (Eyring et al., 2016; Jungclaus et al., 2016) aiming at contributing to the following IPCC assessment. Robust knowledge about multi-centennial climate variability grants understanding about the responses of the climatic system to the radiative forcings in the past.

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