DKRZ resources request 2022 for project: ILModelS – first semester 2021 report

Project Title:

IMpact of land model depth on climate and climate change scenario Simulations (ILModelS)[1]

Project coordinator at DKRZ:

Johann Jungclaus (Max Planck Institute for Meteorology)

Principal Investigators:

Fidel González-Rouco (Universidad Complutense de Madrid),
Johann Jungclaus (Max Planck Institute for Meteorology),
Stefan Hagemann (Helmholtz-Zentrum Hereon)
Elena Garcia-Bustamante (CIEMAT)**,**

Participants:

Norman Steinert (Universidad Complutense de Madrid),
Philipp de Vrese (Max Planck Institute for Meteorology),
Stephan Lorenz (Max Planck Institute for Meteorology)
Félix García Pereira (Universidad Complutense de Madrid),

Collaborators:

Camilo Melo-Aguilar (Centro Oceanográfico de Baleares - IEO)

Report period: **1.1.2021 - 31.07.2021**

Content

[1] In the current funding period, the name of the project has been adapted to "Global and Regional Impacts of using more realistic Land Modelling on Historical and Climate Change scenario Simulations (GReatModelS)"

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 (Reick et al., 2021), and the MPI-ESM (Hagemann et al., 2013; Mauritsen et al., 2019). There is evidence suggesting that the simulation of subsurface thermodynamics in current Earth System Models (ESMs) might not be accurate enough (Smeron & Stieglitz, 2006; Alexeev et al., 2007), since typically the Land Surface Model (LSM) component 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 ESMs use BBCPs that are shallower than 10 m depth (Cuesta-Valero et al., 2016; Burke et al., 2020). Previous work related to GReatModelS has shown that a realistic representation of the subsurface hydro-thermodynamic regime is of importance when assessing continental heat storage and heat fluxes at decadal to multicentennial time scales (Cuesta-Valero et al., 2021), and both air-land surface temperature coupling (Melo-Aguilar et al., 2018; Melo-Aguilar, 2020) and soil moisture distribution (Roldán et al., 2020; Pérez-Pérez et al., 2021) at various time scales.

Progress of work in the GReatModelS project

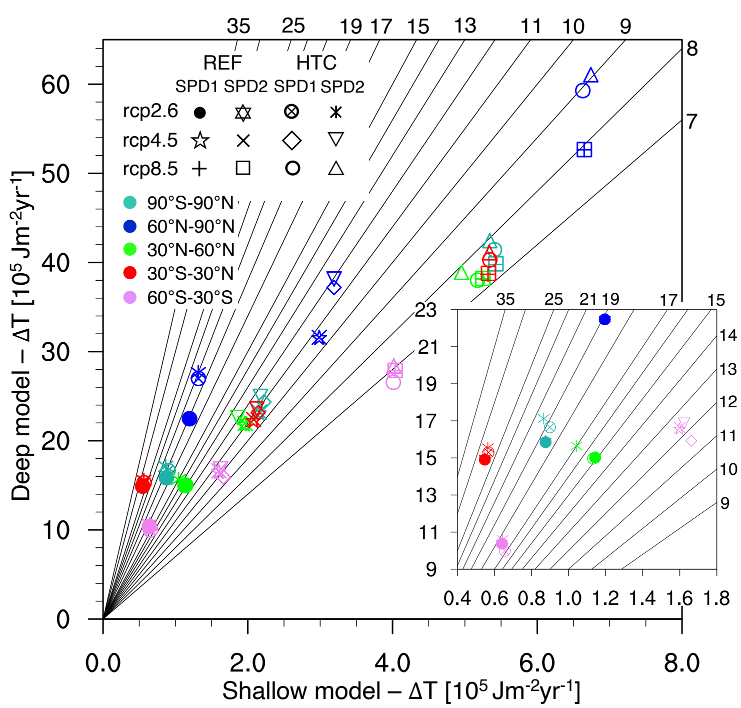

Figure 1. Regional annual mean heat content change ΔQ [10^5 $Jm^{-2}yr^{-1}$] for the shallow (x-axis) vs the deep (y-axis) model for different soil hydrological conditions of HTC and SPD in the RCP2.6, RCP4.5 and RCP8.5 scenario projections. Black lines and the corresponding number at the right and top axis correspond to multipliers between the shallow and deep configurations. The inset provides a zoom into the lower part of the scale. From Steinert et al. (2021a).

Computational and scientific efforts in GReatModelS, devoted to assessing the influence of an improved subsurface physical representation in the standalone JSBACH LSM, have been translated into the submission of three papers in 2021 (González-Rouco et al., 2021; Steinert et al., 2021a; Steinert et al., 2021b), all of which are currently accepted or in minor revision. First, standalone simulations of JSBACH with gradually increasing BBCP-depth permitted the realization of the first consistent comparison of analytical and simulation-based estimates of suitable land depth in climate models on climate-change timescales (Steinert et al., 2021b), in contrast to previous studies that mainly focused on the subsurface propagation of an annual wave (e.g., Smeron & Stieglitz, 2006; Alexeev et al., 2007). Agreement between the numerical and analytical frameworks can only be reached by adapting the analytical signal to the timescale and magnitude of projected anthropogenic warming. This gives an accurate and more confident estimate of the required BBCP depths in LSMs, assesses the relative bias in too shallow LSMs, and provides a numerical framework to be adjusted to different warming signals. Steinert et al. (2021b) conclude that for an unbiased representation of the subsurface temperature propagation with depth, a BBCP of at least 170 m is required to simulate the ground climate for anthropogenic warming adequatelly.

The knowledge derived from Steinert et al. (2021b) is put to use in González-Rouco et al. (2021). The thermal response to imposing a deeper BBCP at 1400 m in preindustrial control, historical (1850-2005) and RCP scenario (RCP) simulations is explored, with a particular focus on the subsurface temperature structure and energy storage. Using a deep model configuration triggers a relative cooling on subsurface temperatures, which ranges from 0.5 to 1.5K over most land areas depending on the scenario, illustrating the potential warm bias in too shallow CMIP6 models. This cooling is more acute at high latitudes, which agrees with polar amplification. Furthermore, imposing a deeper BBCP allows the subsurface more heat storage space, which results in 3 to 5 times more heat stored during the historical period, increasing to 40 in the RCP8.5 scenario.

In the frame of a more realistic BBCP depth representation, Steinert et al. (2021a) provide insight into the sensititvity of the response of the standalone JSBACH to improved hydro-thermodynamical features, particularly relevant for high-latitude cold region physical processes. Both the effect of implementing hydrological and thermodynamical coupling (HTC) and the use of different soil parameter datasets, including water storage space and root zone depth (SPD1/SPD2) are considered with shallow and deep BBCP configurations, respectively. Four HTC mechanisms are introduced following Ekici et al. (2014): freezing and melting of soil water, allowance for supercooled water, an improved five-layer snow model, and time-dependent soil thermal properties. Results show that introducing HTC produces even greater temperature differences between the shallow and the deep LSM configurations at regional scales. A more realistic snow layering produces an enhanced insulation, warming the high northern latitudes with respect to the reference model. Water phase changes and supecooled water inclusion contributes to a net cooling.

In addition, moisture-dependent soil thermal properties yield a relative cooling effect over arid areas of the Northern Hemisphere. Differences imposed from variations in the soil parameter datasets cause relatively low temperature response but have larger impact on regional soil moisture distribution, which becomes important in the frame of HTC. These diiferences have an impact also on energy storage, as shown in Figure 1. HTC inclusion is specially relevant to better represent cold-region dynamics, including the representation of permafrost in the historical period and scenarios (Fig. 2). Permanently frozen soil areas store a great amount of carbon. A release of this carbon from the soil into the atmosphere would fuel global climate warming by a potential enhancement of human-induced greenhouse gases by 22 – 40% (Comyn-Platt et al. 2018). For this reason, future simulations with improved high-latitude soil physics in JSBACH will focus on assessing the permafrost vertical structure and spatial extent, with a particular focus on fully-coupled model conditions under different SSP scenarios (see the corresponding resource request attached to this report).

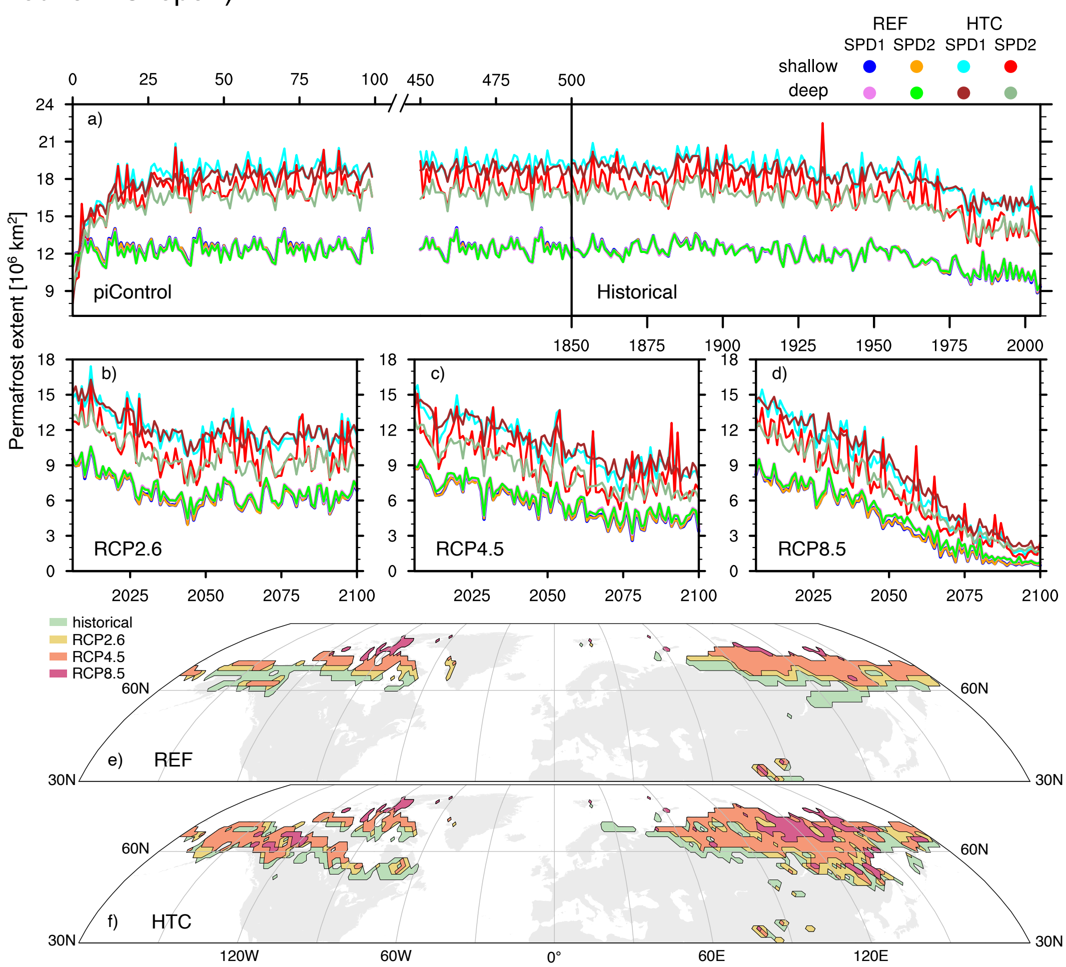

Figure 2. Permafrost extent (10^6 km^6; 45–90N) in different soil hydrological HTC and SPD conditions (colors) from PIC and HIS (a) to RCP2.6, RCP4.5 and RCP8.5 (b-d) forcing conditions. Spatial permafrost in JSABCH-REF (e) and JSBACH-HTC (f) in the deep model with SPD1 for decadal means of HIS (1980-1990, green), RCP2.6 (2090-2100, yellow), RCP4.5 (2090-2100, orange) and RCP8.5 (2090-2100, red). From Steinert et al. (2021a).

Other lines of progress and planned work

We have additionally dedicated our computational resources to the production of fully-coupled MPI-ESM simulations with the deep version of JSBACH for piControl, historical and future scenario simulations. Our first approach has been limited to running both a shallow and a deep simulation, without taking into account HTC or SPD changes. This enables an evaluation of the net effect of every climate component on the climate variability simulated using a deeper and more realistic soil module. Furthermore, we have performed a fully-coupled simulation of the last 2000 years (last 2k, 0-1850) with a deep LSM, fulfilling forcing requirements of PMIP4 simulations (Jungclaus et al., 2016). We intend to extend the analysis to the historical period and some RCP scenarios to depict an image of the abrupt warming of the last century in the context of the climate of the last two millenia (PAGES 2k, 2015). Preliminary analysis shows a clear response of temperature variability to external forcing, especially volcanic and to a lesser extent, solar (Fig. 3). Their shared contribution seems to mimic some centuries of warm temperature anomalies, coinciding with the Medieval Climate Anomaly (MCA, 950-1250), and a transition to a colder period, the Little Ice Age (LIA, 1450-1850), where volcanic activity was notorious (Fernández-Donado et al. 2013).

Additionally, a new version of JSBACH (HTCp hereafter), developed by MPI-M "The Land in the Earth System" Department (de Vrese et al., 2021; de Vrese & Brovkin; 2021), is currently being tested in the frame of GreatModelS. HTCp represents an evolution of HTC (Ekici et al., 2014), adapting soil physical processes, such as the interaction between soil hydrology and vegetation, the treatment of supercooled water, the representation of percolation and drainage by including the effect of soil ice content on the hydrological and biophysical properties of the soil, and the land surface-atmosphere coupling, to the couple mode of MPI-ESM (de Vrese et al., 2021; de Vrese & Brovkin, 2021). It counts also on an enhanced vertical discretization in the first meters of the soil, which aims to better represent thermo-hydrodynamical processes near the surface. After the initial test phase, we plan to conduct last 2k, historical and scenario experiments, with a particular focus on assessing the evolution of the high-latitude climate dynamics under a more realistic vertical high resolution deep soil representation.

Contributions of the collaboration

Apart from the aforementioned publications (Melo-Aguilar et al., 2020; González-Rouco et al. 2021; Steinert et al., 2021a; Steintert et al. 2021b), the collaboration between the Spanish and the German teams in GReatModelS has brought relevant scientific outcomes. It yielded to a PhD dissertation (Steinert, 2021) that will be defended in Universidad Complutense de Madrid and is supervised by Dr. Johann H. Jungclaus, from MPI-M, and a MSc Thesis (Pérez-Pérez, 2021) that was fully constructed from JSBACH standalone simulations data. An extension of the work in Steintert (2021) was granted a prize in the

"PhDay Físicas UCM 2019". Furthermore, the collaboration has facilitated the pre-doctoral stays at MPI-M in Hamburg for Norman Steintert (October-December 2020) and Camilo Melo-Aguilar (September-November 2019), which were essential for the accomplishments of their dissertations and fostered the collaboration between the UCM and the MPI. Other group members also had the chance to enjoy some short stays either at Hamburg or Madrid, that promoted the scientific discussion and development of the project. These cross-stays are intended to continue in the future, so that the Spanish team has applied for the Spanish Science Ministry call "ILINKB2021", which funds international collaboration initiatives.

Further, the group has also participated in multiple congresses and conferences (listed in "References") which has made it possible to disseminate the joint activity carried out under GReatModelS.

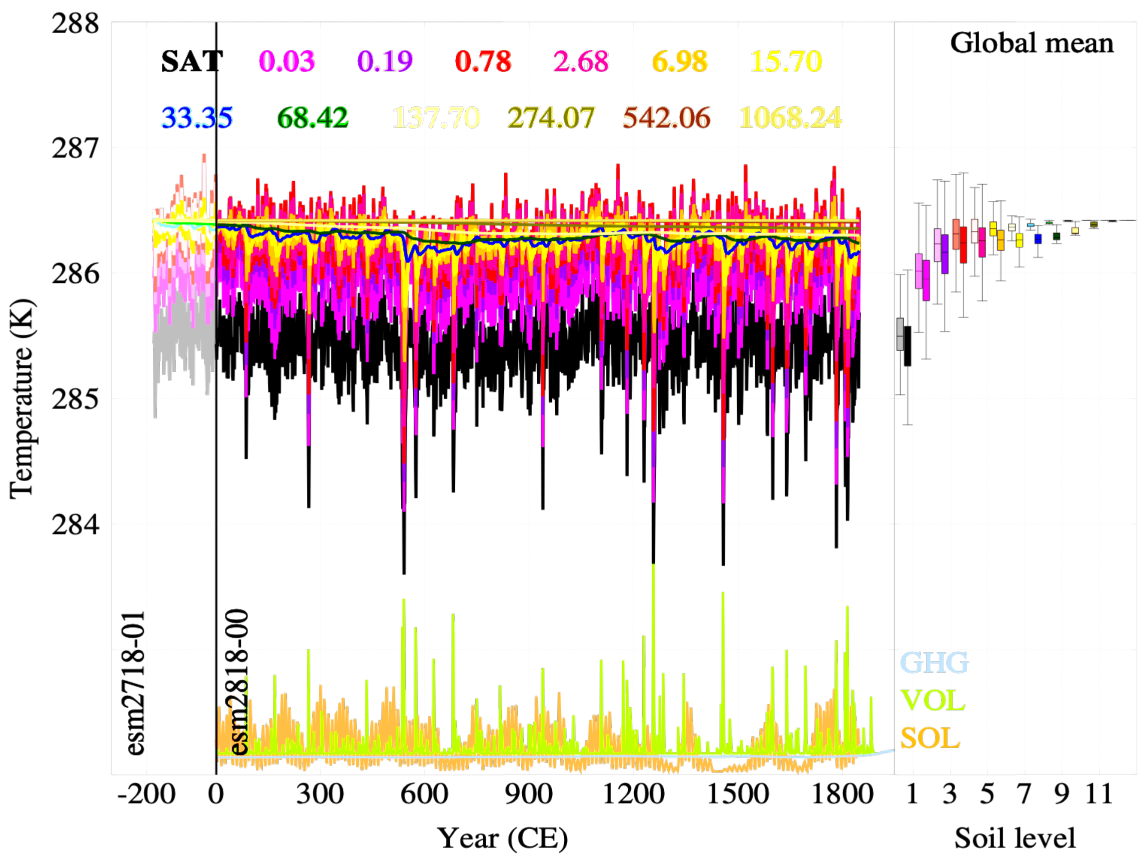

Figure 3. Global mean temperature over land for surface air (SAT) and subsurface layers from 1 to 12 (see gradient of color). First 180 years (pale colors) correspond to a last 2k control simulation (esm2718-01). Temperature values at year 180 are used as initial conditions for a fully-forced last 2k simulation (intense colors, esm2818-00). Time evolution of volcanic (VOL), solar (SOL) and greenhouse gases (GHG) forcings are also depicted. Unpublished material.

Acknowledgements

The Spanish team would like to highlight the great importance of DKRZ/MPI in supporting this project with its resources. The deeper insight in understanding the role played by the LSM in fully-coupled climate models provided by GReatModelS would have not materialized without the computational hours and storage capacity granted by DKRZ/MPI. We are aware of our commitment to manage these resources responsibly. In that sense, it is important to mention that we have expanded the use of the archiving system in order to address the comments of the Scientific Steering Committee from previous allocations. Our plan is to push experiment output to the new Hierarchal Storage System (HSM), keeping track of our resource occupation comprehensively.

Last, we would also like to thank the last year's reviewers for the revision process and their constructive feedback on the report. We attempted to include all the suggestions we were provided with, so as to improve this report.

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(project team members in black; ** publications developed in the frame of ILModelS/GReatModelS)

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Outreach activity in the frame of ILModelS/GReatModelS:

** **González-Rouco, J. F., E. García-Bustamante, N. Steinert, S. Hagemann, S. Lorentz, J. Jungclaus, P. de Vrese, C. Melo-Aguilar,** and J. Navarro: "Impact of land model depth on long- term climate variability and change" presented (oral) at the Fourth International Conference on Earth System Modelling (4ICESM), Hamburg, Germany, 2017a.

** **González-Rouco, J. F., E. García-Bustamante, N. Steinert, S. Hagemann, S. Lorentz, J. Jungclaus, P. de Vrese, C. Melo-Aguilar**, and J. Navarro: "Impact of land model depth on long- term climate variability and change" presented at (poster) at the 1st PMIP4 Conference, Stockholm, Sweden, 2017b.

** **González-Rouco, J. F.., E. García-Bustamante, S.Hagemann, S. Lorentz, J. Jungclaus, P. de Vrese, C. Melo-Aguilar,** J. Navarro, and **N. Steinert**: "Impact of Land Model Depth on Long Term Climate Variability and Change" presented (poster) at 2017 Fall Meeting, AGU, New Orleans, LA, 11-15 Dec. 2017c.

** **González-Rouco, J. F., E. García-Bustamante**, J. Navarro, **C. Melo-Aguilar,** and **N. Steinert**: "Model-data comparison over the last millennium: influence of land model depth", presented at (oral) IGEO Meeting, Madrid, Spain, 2020b

** **Melo-Aguilar, C., J. F. González-Rouco, E. García-Bustamante**, and J. Navarro. "Last Millennium atmosphere and soil temperature coupling in surrogate climates: implications for borehole temperature reconstructions" presented at (oral) 2017 EMS Annual Meeting, Dublin, Ireland, 2017.

** **Melo-Aguilar, C., J. F. González-Rouco, E. García-Bustamante**, J. Navarro, and **N. Steinert**: "Impacts of long-term land use land cover changes on borehole temperature reconstructions" presented at (poster) 2018 EGU General Assembly, Vienna, Austria, 2018a.

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