Report: Exploring modeled climate variability in past cold and warm states of the Earth System

Project: 1479

Project title: EXPLAINstates

Principal investigator: Julia Brugger, Kira Rehfeld

Allocation period: 2025-01-01 to 2025-12-31

Project overview

Within EXPLAINstates, we explored two of the CMIP7[1] fast track experiments, *abrupt-127k* (representing the last interglacial, LIG) and *abrupt-0p5CO2*, from a paleoclimate modeling perspective using two state-of-the-art climate models. This spans an as-warm-as-present time period, and a simulation that is expected to be as cold as the Last Glacial Maximum 21 thousand years ago. These experiments are of great importance for a better understanding of the effects of various forcing factors on the climate system, their interactions and feedback processes. Exploring the last interglacial also helps to test the ability of state-of-the-art climate models to simulate near-future warming. In this way, these experiments contribute to a better understanding of current and future climate change.

Report on the first project phase

Last interglacial simulations with ICON XPP

The abrupt-127k experiment starts on a pre-inudstrial simulation for which orbital parameters and greenhouse gases are adjusted to LIG levels. For getting ICON XPP ready to run this experiment, it first needed to be code implemented to vary orbital parameters. This step was taken by Martin Köhler (DWD), in close exchange with us. His implementation of the VSOP87 model showed not only to be relevant for paleo applications, but it also lowered the top-of-atmosphere shortwave (TOA) radiation bias by -4W/m2 and temperature bias of pre-industrial (PI) simulations by -0.5°C in ICON NWP.

Our simulations built on simulations with a LIG orbital configuration from Sebastian Wagner (Helmholtz Zentrum Hereon), run with ICON XPPv1.0 (from 2024/7), including VSOP87 for radiation on a resolution of R2B4/R2B6 (atmosphere/ocean). We first extended his LIG simulations and pre-industrial simulations for several years to write the output we needed for our analysis. We then started a LIG simulation from the PI simulation, here not only changing orbital values, but also adjusting greenhouse gases to LIG values, based on the description of the LIG experiment of PMIP4 (Otto-Bliessner et al., 2021). Other boundary conditions (solar constant, ice sheets (prescribed), vegetation (prescribed), aerosols) were kept at pre-industrial values. The simulation ran for 150 years, sufficiently long as described in Sime et al. (2025). We added some model years with daily output for further analysis later.

Comparing our abrupt-127k simulation with the pre-industrial simulation, we find patterns of the difference in TOA radiation in agreement with published LIG simulations (Otto-Bliesner et al., 2021). The Arctic summer increase of TOA radiation of 50-75 W/m^2 agrees particularly well. Annual global mean temperatures are decreased by 0.3 K for the simulation including LIG orbital values compared to PI, and by 0.47 K when including LIG orbital values and greenhouse gases. This disagrees with proxies showing a temperature increase for the LIG by 0.5 to 1.5 K. Exploring Arctic seasonality, we find a temperature increase of 4 K in July, a decrease of 3 K in January, but an Arctic cooling in the annual mean, comparing our abrupt-127k simulation to the PI simulation. Arctic sea ice changes little in summer, but is increased in winter compared to PI. Overall, this results in an annual sea-ice expansion compared to PI. We therefore attribute the simulated temperature decrease (disagreeing with proxy data) to an insufficient sea-ice feedback and too low Arctic amplification in the ICON-XPP version used. This is a finding with major implications for future simulations with ICON-XPP,

[1]Coupled Model Intercomparison Project Phase 7, see https://wcrp-cmip.org/cmip-phases/cmip7/

and is therefore relevant for the ongoing improvement and further development of ICON-XPP.

These first results were presented on the ICCARUS conference in Offenbach (March 2025)[2] and the D·A·CH 25 conference in Bern[3] as a poster and at EGU General Assembly in Vienna in a talk (May 2025)[4]. Next steps are simulations with two more recent ICON-XPP versions for comparison and several sensitivity tests.

LGM - abrupt-0.5xCO2 analogy with MPI-ESM-wiso

In the second part of the project, we investigate whether the CMIP7 fast track experiment *abrupt-0p5CO2* state can serve as an analog for the Last Glacial Maximum (LGM, ~21,000 years ago; its simulation denoted as *lgm*) and where the analogy breaks. Existing simulations from various models show a comparable cooling response in global mean temperature, though the forcing differs. The *abrupt-0p5CO2* experiment has the same boundary conditions as the *piControl* experiment but with half the atmospheric carbon dioxide concentration (CO_2 = 142 ppm). For the *lgm* experiment, atmospheric greenhouse gas concentrations are reduced (CO_2 = 190 ppm, CH_4 = 375 ppb, N_2O = 200 ppb), large ice-sheets are introduced over Northern Hemisphere land masses and the orbital configuration is modified slightly.

We successfully ran an *abrupt-0p5CO2* experiment for 1000 years with the isotope-enabled version of MPI-ESM, MPI-ESM-wiso. Together with our cooperation partners, Marie Kapsch (MPI Hamburg) and Alexandre Cauquoin (UTokyo), we have successfully implemented a simulation of the LGM, which has not been consistently realized before with this model. The following 3,000-year-long *lgm* simulation was performed by Alexandre Cauquoin and was only extended by 30 years from us for our own analysis purposes. The same applies for the *piControl* simulation, which is used as a reference. About 20 simulation years were needed for test and debugging runs.

In the global mean response to the forcings, we observe a cooling of about −2.51 K and -3.47 K for *abrupt-0p5CO2* and *lgm*, respectively. The local cooling patterns demonstrate the different nature of the forcings, which also translates to other climate variables, as the simulated isotopic composition of precipitation. In a preliminary comparison to proxy data from climate archives from the LGM, the RMSE scores are better for the *lgm* (4.59‰ vs 4.91‰). This is mainly due to missing polar amplification in Antarctica in the *abrupt-0p5CO2* experiment, tentatively indicating that climate proxies are able to capture state-specific characteristics beyond the global mean.

These results were shown at the D·A·CH 25 conference in Bern[2]. Currently, we are refining the statistical methods of the model-data comparison and running sensitivity experiments to quantify the different forcings better.

References:

Otto-Bliesner, B. L., Brady, E. C., Zhao, A., Brierley, C. M., Axford, Y., et al.: Large-scale features of Last Interglacial climate: results from evaluating the *lig127k* simulations for the Coupled Model Intercomparison Project (CMIP6)–Paleoclimate Modeling Intercomparison Project (PMIP4), Clim. Past, 17, 63–94, https://doi.org/10.5194/cp-17-63-2021, 2021.

Sime, L. C., Diamond, R., Stepanek, C., Brierley, C., Schroeder, et al.: A sea ice free Arctic: Assessment Fast Track *abrupt-127k* experimental protocol and motivation, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-3531 , 2025.

[2] https://www.dwd.de/EN/specialusers/research_education/seminar/2025/iccarus2025/final_programme_en.pdf

[3] https://dach2025.oeschger.unibe.ch/, https://www.conftool.com/dach2025/index.php?page=browseSessions&form_session=37

[4] Rehfeld, K., Brugger, J., Racky, M., Baudouin, J.-P., Jungclaus, J., Kelemen, F. D., Lorenz, S., Wagner, S., and Köhler, M.: First steps towards paleoclimate constraints for climate prediction and projections with the ICON model, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-13114, https://doi.org/10.5194/egusphere-egu25-13114, 2025.