Joint state-parameter estimation for the Last Glacial Maximum with CESM1.2

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In Short

- The project provides state-of-the-art reconstruction of global Last Glacial Maximum (LGM) climate with uncertainty bounds
- Ensemble climate integrations are done with the Community Earth Earth System Model (CESM v1.2) with perturbed-physics and varying forcings experiments
- Homogenized multi-proxy observations compiled within the scope of PALMOD project are assimilated into CESM v1.2

This compute proposal is set within the framework of the BMBF-funded project PALMOD, now in its 3rd year whithin its 1st 4-yr phase. In this compute project, framed within the 1st phase, we use a coupled atmosphere-ocean global climate model (AOGCM), the Community Earth System Model (CESM v1.2) to run ensemble climate simulations at the Last Glacial Maximum (LGM, 19–23 kyr BP). The background ensemble spread is generated by perturbing uncertain forcings (including flux terms) and model physics. The most recent compilation of multiple paleo-climate proxies for LGM, conducted within the framework of PALMOD, is then assimilated to obtain the climate reconstruction, which includes an estimate of the posterior (in a Bayesian sense) uncertainty.

The approach allows for quantitative model-data inter-comparison, and the posterior climate estimates support the study of climate relations (e.g. atmospheric and oceanic teleconnections) in a context that strongly differs from the current climate, and uses an optimal combination of ensemble model runs and proxy observational information. This provides a further insight into the climate variability than the single evaluation of the proxy data or model simulations. Thus, this computing project is hoped to contribute to the further understanding of global climate variability, and to constrain future climate projections under a globally warming Earth.

The coupled climate model consists of components for the atmosphere, ocean, land and sea ice, which communicate with one another via a central coupler module. The model uses a regular Finite Volume grid with horizontal resolution of $\sim 4.0°$ for the atmosphere and land, and a displaced pole (centered at Greenland) $\sim 3°$ irregular Finite Volume grid for ocean and sea ice. The vertical representation of the atmospheric model comprises 30 layers in a hybrid sigma-pressure system. The ocean has 60 vertical levels with thicknesses increasing with depth. The major ensemble experiment runs at LGM for 400 years with ensemble members branching from a common simulation, which has previously brought to equilibrium. The control variables (forcings and perturbed physics) are perturbed to generated the ensemble spread (the background), so each ensemble member converges torwards its own new equilibrium. It is with this equilibrium ensemble, where only internal variability remains, that the assimilation of the multi-proxy database is conducted.

Likely, the most recent and careful dynamical reconstruction of the global ocean during the LGM is [2], which uses an ocean-only global circulation model (the MITgcm), so it cannot account for atmospheric feedbacks. Thus the question remains open about whether a fully coupled global Earth system model (ESM) would yield a similar reconstruction, given the state-of-the-art homogeneised multi-proxy data as being compiled in PALMOD. This calls for this current project.

In previous work, we have conducted preindustrial ensemble assimilation experiments, which have shown satisfactory results and indicate that even for multidecadal and longer timescales the nonlinearity between the control variables and the dual of the observation space hampers the application of standard (ensemble) linear Kalman-based assimilation methods. Our analyses in a previous phase of this project show that an iterated, Gauss-Newton, Kalman smoother based on local finite difference sensitivity estimates converges in the evaluated experiments, and leads to reduced cost function values and simultaneous computational saving if the number of control variables is low [1]. The degree of non-linearity varies with location, and for example, it is very high in the North Atlantic where there is a substantial amount of existing proxy data for LGM [1]. Also, previous sensitivity tests have served for parameter screening. An identical twin experiment with observations from a true run taken at MARGO locations [3] showed that not all parameters (in a selected set of parameters for cloud processes, sea ice and ocean diffusion) were identifiable with preindustrial forcings. On the other hand and importantly, care must be taken to have a consistent solution for identifiable control variables, and the need of adequate regularization has been emphasized.

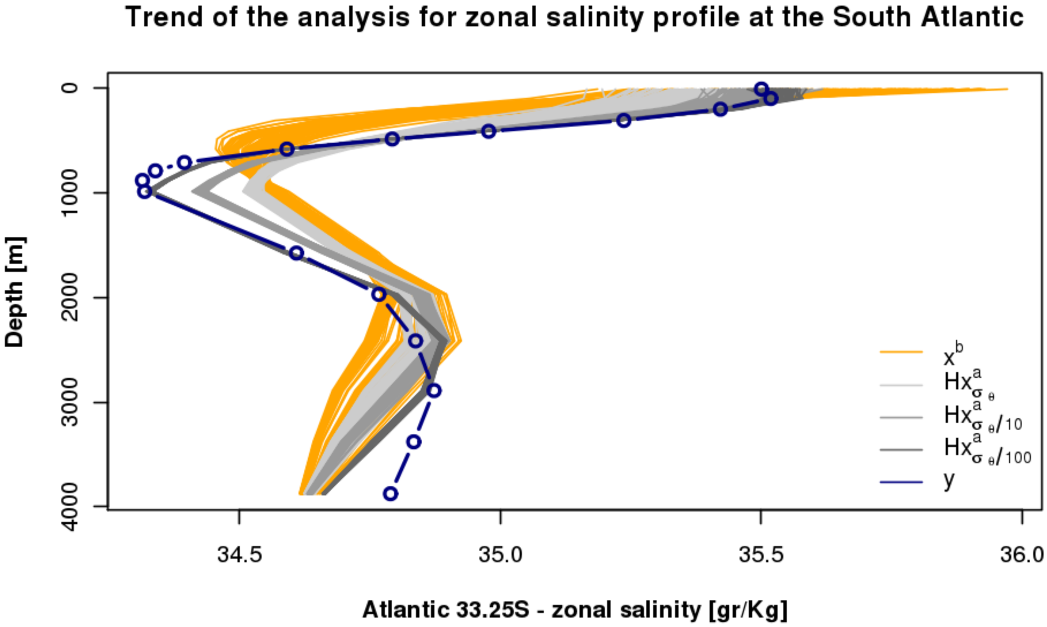

Figure 1: *Sensitivity of assimilation results to observational uncertainty in current climate. Orange lines are the background ensemble of zonal mean salinity in the South Atlantic (20-yr average). Blue line with circles are the target zonal mean salinity observations, taken as the mean of 4 previous climate reanalysis for present conditions (C-GLORS, ECCOv4, ORAS4, SODA). Clear gray lines are ensemble results with initially estimated observational uncertainty. Observational standard deviation divided by 10 and 100 leads to the medium gray and dark gray analysis estimates, respectively.*

In this sense, one of our early examples in this project remains illustrative on the importance of regularization. In the experiment, we first built a preindustrial background climate consisting of 20-yr annual means of a perturbed physics ensemble. As target, we assimilated corresponding 20-yr annual mean zonal salinity profile in the South Atlantic (related to the AMOC). These "observations" of salinity profiles were constructed as an average from previous existing reanalyses (C-GLORS, ECCOv4, ORAS4, SODA). Figure 1 summarizes the sensitivity of the posterior mean zonal salinity in the South Atlantic to the uncertainty in the observations errors. The plot shows that it is possible to very much approach the observations as their uncertainty is reduced (and regularization decreases accordingly). However, the augmented system shows that the jointly estimated parameters (not shown) give unrealistic values for an over-fitted ocean salinity, which leads to model divergence. In summary, previous work has set the basis for a) the assimilation methods, b) construction of targets for the climate reconstruction further that the point-wise model-observation comparison, and c) sound construction of uncertainties in both model background and paleo-climate proxies. These three points work together and the project has all ingredients to lead to an awaited reconstruction of the Last Glacial Maximum global climate with state-of-the-art Earth system modelling and paleo-climate proxy compilation.

WWW

https://www.marum.de

More Information

[1] J. García-Pintado, A. Paul *GMDD* (2018). doi: 10.5194/gmd-2018-48

[2] T. Kurahashi-Nakamura, A. Paul, M. Losch *Paleoceanography* (2017). doi: http://10.1002/2016PA003001

[3] MARGO Project Members [C. Waelbroeck, A. Paul, M. Kucera, A. Rosell-Mele, M. Weinelt, R. Schenider, A.C. Mix and 45 others] *Nature Geosci.* **2**, 127–132 (2009). doi: 10.1038/ngeo411

Project Partners

AWI, CAU, DKRZ, GEOMAR, HZG, IfBM, University of Mainz, FUB, KIT, TROPOS, MARUM, MPI-C, MPI-M, MUN, University of Bonn / HErZ, PIK, University of Hamburg

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