Project: **1442**

Project title: **Large ensemble modeling of Earth system on long time scales**

Principal investigator: **Alexander Robinson**

Report period: **2024-05-01 to 2025-04-30**

Summary of Progress

Over the past year, our project at DKRZ has focused on advancing the understanding of large-scale ice sheet dynamics, stability thresholds, and feedbacks under varying climatic conditions, from the Holocene to projected future warming scenarios. We had a slow start as we initially focused on porting the model(s) to Levante and hiring personnel took longer than expected. Most of the work performed until now has been focused on stand-alone ice-sheet simulations using Yelmo, as further development and testing has been determined to be needed for CLIMBER-X. We leveraged the computing resources at DKRZ to run ensemble simulations, transient spin-ups, and perturbation experiments. These efforts have directly contributed to several publications currently in preparation.

Key Achievements

1. **Evaluation of Spin-up Strategies for Ice Sheet Models (Blasco et al., in. prep.)**
   We systematically evaluated different model spin-up strategies incorporating interannual climate variability in forcing simulations using Yelmo. Typically ice-sheet models are spun up with steady-state boundary conditions. However, it is an open question as to what extent switching to projections with forcing that contains interannual variability (ie, yearly output from ESMs) will cause model drift unrelated to the forcing. We are therefore testing different spinup strategies with and without variability, and the continued simulations where variability is turned on or off. So far, results show that key differences can occur as a result of these different spinup strategies and that special care must be taken to ensure consistency from spinup to projection. This work is ongoing and more simulations are needed to evaluate the different approaches more clearly.

2. **Projections of Antarctic ice sheet sea-level contribution in the future (Juarez-Martinez et al., in prep.)**

   Using our regional ice-sheet model setup, Yelmo coupled to the new FastIsostasy bedrock isostasy model, we are in progress of performing ensembles of simulation to test feedbacks between ice-sheet retreat and isostasic rebound. In particular, it is known that uplift of marine regions can reduce grounding-line retreat (negative feedback). An open question is if the isostatic response can also change the ocean depth at which water accesses the shelf. These are processes that act on longer timescales and deep uncertainty exists. Therefore ensembles are used to test parametric dependence and the robustness of the mechanisms. After initial calibration, a preliminary ensemble of simulations out to year 3000 has been performed. This ensemble needs to be refined to test specific parameter ranges of interest and is the next step.

3. **Greenland Ice Sheet Thresholds from Past to Future (Gutiérrez-González et al., in prep.)**

   We performed a comprehensive set of equilibrium simulations with the Yelmo ice-sheet model coupled to the regional climate model REMBO and a parameterized ocean melt component. These simulations spanned a wide range of regional summer temperature anomalies, from -12 K (representative of the Last Glacial Maximum) to +4 K relative to present-day conditions. The aim was to construct the bifurcation diagram of the Greenland Ice Sheet and explore its full hysteresis behavior across glacial–interglacial and future warming scenarios. The experiments revealed two distinct tipping points: one near present-day warming levels (+1.2 to +1.6 K) associated with atmospheric feedbacks, and a second, previously unexplored threshold under glacial conditions (-10 to -9 K), driven by dynamic mass loss due to oceanic forcing. These simulations provide new insights into the nonlinear stability regime of the GrIS across a full paleoclimate-to-future range. These simulations are the first step towards running transient ensemble simulations through the Holocene to reconstruct Greenland Holocene evolution.

Use of DKRZ Resources

All simulations were conducted on the Levante cluster at DKRZ. We utilized ~15.000 node-hours and so far produced ~5 TB of model output. The computational efficiency and scalability of our codes were optimized for the Levante architecture, enabling us to test a range of model configurations and scenarios.

Outlook

In the coming year, we aim to finalize the above-mentioned manuscripts and incorporate improved physical processes into Yelmo (e.g., subglacial hydrology, improved surface mass balance on long timescales). Using the calibrated model, we will also contribute to ongoing intercomparison project efforts that are directly related to our own project goals. We will also begin to run experiments using CLIMBER-X when we are confident it is production ready. Continued access to DKRZ resources will be crucial for conducting perturbed-parameter ensembles and Holocene reconstructions and future projections of ice sheet evolution.