

Project: **1442**

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

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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. This year we largely focused on stand-alone ice-sheet simulations using Yelmo, as the personnel were in place and key project deadlines were met. However in parallel, we have also begun to run the coupled CLIMBER-X-Yelmo simulations with a focus on the period of the Last Glacial Maximum until today. We have determined that the model functions well technically, but that calibration of the ice sheets is a continuing challenge. We leveraged the computing resources at DKRZ to run ensemble simulations, transient spin-ups, and perturbation experiments. These efforts have directly contributed to several studies that are published or currently in preparation.

Key Achievements

1. Evaluation of Spin-up Strategies for Ice Sheet Models

Blasco et al., Climate variability eases West-Antarctic Ice Sheet collapse and opens new retreat paths, submitted.

Projections of how fast the West Antarctic Ice Sheet will melt typically use climate model simulations that may not fully capture the year-to-year and decade-to-decade climate fluctuations observed in the real world. These natural climate fluctuations—driven by ocean currents, weather patterns, and other factors—can potentially lead to faster or slower ice-sheet responses due to non-linear interactions between climate and cryosphere. We investigated whether these climate fluctuations affect predictions of when the West-Antarctic ice sheet might collapse and raise sea levels. Using 30 years of climate observations (1990-2019), we ran 100 different simulations of the Antarctic ice sheet over 1500 years, each with randomly varying climate conditions drawn from real observations. We found that climate fluctuations can change the timing of ice-sheet collapse by more than a century. Ocean temperature fluctuations drive this uncertainty. Random warm pulses in ocean temperatures due to year-to-year changes in ocean circulation can trigger ice retreat through new pathways in northern West Antarctica that are not found in standard predictions.

2. Projections of Antarctic ice sheet sea-level contribution in the future

Juarez-Martinez, A., Robinson, A., Swierczek-Jereczek, J., Blasco, J., Alvarez-Solas, J. and Montoya, M.: Parameterizing tidal-water intrusions in long-term Antarctic ice-sheet projections, in review.

Antarctica is home to the largest ice sheet on Earth, and contains enough ice to significantly raise global sea levels. Most of this ice is grounded on land, but at its margins ice floats on the ocean forming ice shelves. Ice loss in Antarctica is mainly caused by ocean-driven melting of ice under the ice shelves, which can enhance ice discharge. One important factor that has been neglected up to now in ice-sheet models is the effect of tides in such sub-shelf melting. Tides cause relatively warm ocean water to intrude under Antarctica's grounded ice, increasing melting at the base of the ice shelves. Even small increases in melting at the boundary of grounded and floating ice can have large effects on the ice loss and thereby the stability of the ice sheet. Here, we introduce a simple representation of this tidal effect in a state-of-the-art ice-sheet model. Results show that tides could significantly increase ice loss and contribute more to rising sea levels in the future. Understanding these processes is crucial for predicting how Antarctica will respond to climate change and how much it may contribute to global sea-level rise.

3. Greenland Ice Sheet Thresholds from Past to Future

Gutiérrez-González, L., Robinson, A., Alvarez-Solas, J., Tabone, I., Swierczek-Jereczek, J., Moreno-Parada, D., and Montoya, M.: Hysteresis of the Greenland ice sheet from the Last Glacial Maximum to the future, *The Cryosphere*, 20, 1139–1162, <https://doi.org/10.5194/tc-20-1139-2026>, 2026.

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.

[Additional studies in progress]

Gutiérrez-González, L., et al.: Reconstruction of the Greenland ice sheet from LGM to present day, in prep.

Alvarez-Solas, J., et al.: Simulating the hysteresis of all ice sheets on Earth in the past, in prep.

Tesouro Castro, S., et al.: Simulating the Antarctic ice sheet over the last glacial cycle and into the future, in prep.

Use of DKRZ Resources

All simulations were conducted on the Levante cluster at DKRZ. We utilized ~9.000 node-hours and so far produced ~11 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 pursue further studies related to paleo and future simulations, 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 continue to run experiments using CLIMBER-X. Continued access to DKRZ resources will be crucial for conducting perturbed-parameter ensembles and Holocene reconstructions and future projections of ice sheet evolution.