Understanding the mechanisms of natural climate changes from the ocean floor

Development of an Earth system model coupled with a sediment diagenesis model toward long-term paleoclimate simulations

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In Short

- Simulating the history of the atmospheric carbon dioxide (CO_2) concentration during the last glacial cycle is one of the crucial tasks of the PalMod project [1].
- The marine carbon cycle including sediment processes plays a crucial role in the CO_2-concentration history, which demands a process-based chemical sediment model to simulate it.
- The sediment model will also act as a “bridge” between the model and paleoceanographic data showing important fingerprints for the paleo-carbon cycle.
- Time-slice simulations for the preindustrial age, the Last Glacial Maximum (LGM) and Marine Isotope Stage 3 (MIS3) have been done.
- We will extend the established framework to transient simulations to deal with the time evolution of the global climate and carbon cycle.

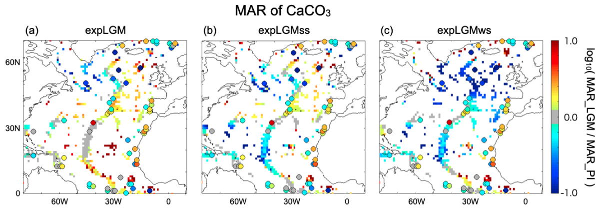
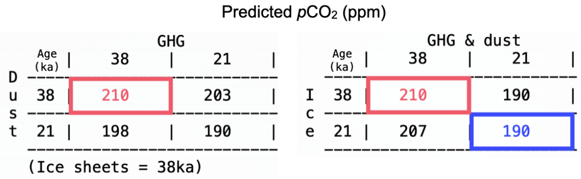


Figure 1: *Mass accumulation rate (MAR) of* $CaCO_3$ *in the upper sediment simulated with MEDUSA. The ratio of MAR in the LGM runs to that in the reference pre-industrial run are shown in a logarithmic scale. Each panel corresponds to a LGM simulation with CESM that has a different AMOC state compared to the modern counterpart: (a) stronger and deeper, (b) stronger and shallower, and (c) weaker and shallower, respectively. The observation-based data [5] are shown as overlaid dots.*


Predicted pCO_2 (ppm)

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                 GHG                              GHG & dust
    Age |    38     |    21     |        Age |    38     |    21     |
    (ka)                                 (ka)
D  -----------------------------      -----------------------------
u   38 |   210     |   203     |   I   38 |   210     |   190     |
s  -----------------------------   c  -----------------------------
t   21 |   198     |   190     |   e   21 |   207     |   190     |
   -----------------------------      -----------------------------
   (Ice sheets = 38ka)
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Figure 2: *Predicted* CO_2 *level in the 38ka experiment (shown in red), the LGM experiment (blue), and in other sensitivity runs (black). To decompose the total effect of different boundary conditions, we altered each of three components of the boundary conditions (greenhouse gas, dust, and ice sheets) separately and systematically.*

The CO_2 concentration in the atmosphere (hereafter, CO_2 level) has been increasing so that it has reached a level that is unprecedented for at least the last 800,000 years. To reliably project the CO_2 level in the future, it is essential to understand the mechanisms for CO_2-level changes and to have comprehensive Earth System Models (ESMs) including the latest knowledge and skills. The last glacial cycle in the last 100 kyrs is considered to be one of the most qualified research targets offering many test cases with large variations in the CO_2 level.

Thus far, comprehensive models are unable to quantitatively reproduce the CO_2-level history in the 100 kyrs. This project will tackle that issue by focusing on the marine carbon cycle that would have played a key role in the variations of the CO_2 level.

In the previous phases of this project, we completed an interactive coupling of the Community Earth System Model version 1.2 (CESM1.2) [2] and Model of Early Diagenesis in the Upper Sediment of Adjustable complexity (MEDUSA) [3] and found that the MEDUSA-coupled CESM outperformed the uncoupled CESM in reproducing the observation-based global distribution of sediment properties through modern-based simulations [4]. The coupling will also contribute to the improvement of model representation of seawater chemistry. Moreover, the sediment model will act as a “bridge” between the ocean model and paleoceanographic data providing an important fingerprint for the paleo-carbon cycle.

We have subsequently carried out key time-slice simulations that will be followed by future simulations in a transient framework.

LGM carbon-cycle simulations with calibrated total inventories of dissolved inorganic carbon (DIC) and total alkalinity: We conducted three fully-coupled LGM simulations that had different global ocean-circulation fields. In addition to glacial boundary conditions based on the PMIP4 protocol, we adjusted the total inventories of DIC and total alkalinity in the ocean to satisfy important observation-based constraints in terms of the size of carbon reservoirs. The simulations successfully reproduced the glacial CO_2 level. This fact has proven the model’s great poten-

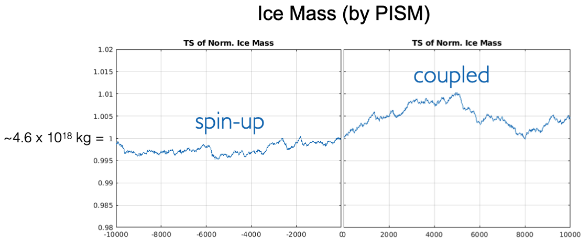

Figure 3: *History of the mass of Greenland ice sheet simulated with PISM. The normalized values are shown for the initial spin up with a stand-alone PISM (left) and for the coupled CESM-PISM run (right).*

tial to simulate the climatic evolution since the LGM including the carbon cycle dynamics. We also explicitly simulate the mass accumulation rate (MAR) of $CaCO_3$ at the ocean floor with MEDUSA. The model–data comparison regarding $CaCO_3$ MAR supported the LGM state with a shallower and weaker AMOC better (Figs. 1). Transient simulations in the coming phase will provide an opportunity to examine the mechanisms for the glacial climate based on the trajectory leading to the modern age.

Preliminary fully-coupled carbon-cycle simulations for MIS3: We applied a similar methodology to intermediate glacial climate states as represented by MIS3. We carried out a simulation for 38ka by giving boundary conditions corresponding to the time slice, and also conducted several sensitivity experiments where we replaced some components of the boundary conditions with the LGM counterpart (Figs. 2). The standard 38ka experiment predicted 210 ppm for the CO_2 level. This predicted CO_2 level was in remarkable agreement with the observation-based reconstruction (210 ppm), implying that the total ocean inventories of DIC and total alkalinity for 38ka would be similar to those in the LGM. The sensitivity runs showed that the change of marine biological production induced by the different dust input, and the change of solubility induced by different sea surface temperature would have played important roles in differentiating the carbon cycle at 38ka from that in the LGM.

Development of an interactively-coupled CESM–PISM model: The time-slice LGM simulations suggested that the evolution of the total inventories of DIC and alkalinity accompanied by the sea-level change would play a key role in the transition from the glacial climate state to the modern state. Considering that the sea-level rise is a direct consequence of the ice-sheet evolution induced by climate changes, it would be fundamental to analyse and discuss the co-evolution of the coupled carbon cycle-ice sheet system. Adopting the Parallel Ice Sheet Model (PISM) as an ice-sheet model, we developed and tested an interactive coupling of CESM and PISM. Following the initial spin up of stand-alone PISM, both the models were coupled asynchronously and sequentially in an offline manner. The behaviors of the modelled climate, ocean circulation, CO_2 level, and Greenland ice sheet were stable and reasonable in the coupled phase (Figs. 3).

In the coming phase of the project, we will extend the current time-slice scheme to a time-evolving framework. We will move on to transient simulations, where we will attempt to reconstruct the transition of the climate system from the glacial regime to the interglacial regime (Termination I). Preparatory work to configure the model for those simulations has been already in progress. We propose a set of time-evolving carbon-cycle experiments for MIS3 as well. Those work will provide other test cases to investigate the responses and roles of the carbon cycle in paleo climate variations.

WWW

https://www.marum.de/Michael-Schulz.html

More Information

[1] `https://www.palmod.de/`

[2] `http://www.cesm.ucar.edu/`

[3] G. Munhoven, *Geosci. Model Dev.*, doi: `https://doi.org/10.5194/gmd-14-3603-2021` (2021).

[4] T. Kurahashi-Nakamura, A. Paul, G. Munhoven, U. Merkel, and M. Schulz, *Geosci. Model Dev.*, doi:`https://doi.org/10.5194/gmd-13-825-2020` (2020).

[5] O. Cartapanis, E.D. Galbraith, D. Bianchi, and S.L. Jaccard, *Climate of the Past*, **14**, 1819–1850, doi:`https://doi.org/10.5194/` (2018).

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

Funding

Federal Ministry of Education and Science (BMBF)