FINAL REPORT PROGRAM LEFE

Program LEFE/ IMAGO	GLACOCEAN: the oceanic circulation at the Last Glacial Maximum	Years 2019 – 2021
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Context

The oceanic circulation is crucial for the climate system. The ocean exchanges heat and carbon with the atmosphere, and the oceanic circulation redistributes it. Correctly understanding and simulating the oceanic circulation at the Last Glacial Maximum (LGM; ~21000 years ago) is a challenge, but is paramount to correctly simulate the climate and carbon cycle.

Objectives / scientific questions

The objective of this project was to improve our knowledge and capability to simulate the ocean circulation at the LGM by focusing mainly on two major drivers of ocean circulation: sea ice formation and the interaction with topography.

Main results

New sea ice LGM compilation We produced new sea surface temperature (SST) and sea ice data, and created a new compilation of sea ice extent data for the Last Glacial Maximum in the Southern Ocean (red line on Figure 1). The previous compilation dated from 2005. The new compilation was included in Lhardy et al. (2021a). The new SST record was included in Civel-Mazens et al. (2021a, b).

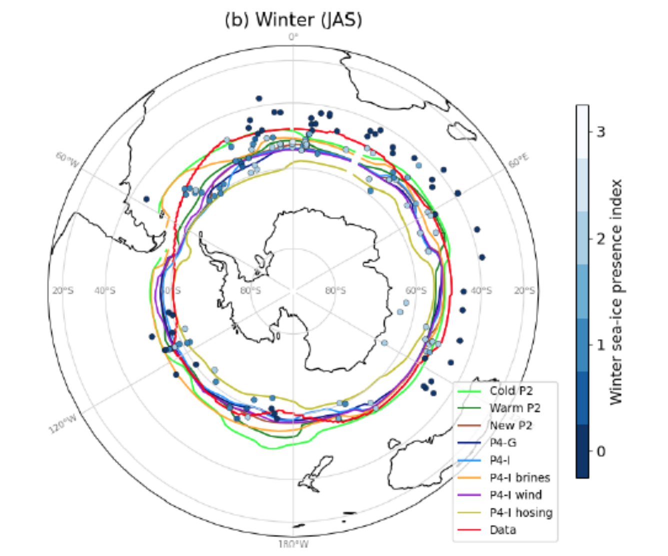
Impact of surface conditions in the Southern Ocean on deep ocean circulation Using an ensemble of simulations from the iLOVECLIM intermediate complexity model, we studied the impact of Southern Ocean surface conditions on oceanic circulation (Lhardy et al., 2021a). We tested the effect of changes of ice sheet elevation, bathymetry, land-sea mask, sea-ice export, formation of sinking water from brine rejection, and fresh water input. Using model-data comparison, we showed that only simulations with a cold Southern Ocean and a quite extensive sea-ice cover present an improved agreement with proxy records of sea ice (Figure 1). Modifying the sinking of dense water from brine release improved ocean circulation, showing the importance of the representation of convection processes.

Accounting for bathymetry and land-sea mask changes We developed a new method to be able to change the bathymetry and land-sea mask in the model using reconstructions. We applied this method to the LGM timeslice (Kageyama et al., 2021; Lhardy et al., 2021b) but also for the Last Deglaciation, showing the impact of bathymetry on global ocean circulation and, thus, on climate (Bouttes et al., 2022).

New mixing scheme in iLOVECLIM We added 3D energy-constrained parameterization of tidal mixing, supplemented by geothermal fluxes, in iLOVECLIM model (Lhardy, PhD thesis, 2022). The new mixing scheme, based on the one already implemented in NEMO, should be more realistic. However, numerical diffusion seems to be too large in iLOVECLIM to obtain meaningful results. This will be further investigated in the future.

PMIP-carbon We initiated the first model intercomparison of carbon cycle simulations for the Last Glacial Maximum. The first results show a large diversity of carbon storage in the main carbon reservoirs, especially the ocean, and the challenge to simulate LGM atmospheric CO_2 in agreement with ice core data (Bouttes et al., 2021; Figure 2; Lhardy et al., 2021b).

Impact of boundary conditions on the LGM carbon cycle Using sensitivity simulations from iLOVECLIM and results from PMIP models, we showed the large impact of boundary conditions on the carbon cycle, especially changes of bathymetry and land-sea mask (Lhardy et al., 2021b). Adjusting the alkalinity to account for the relative change of volume at the LGM induces a large increase of oceanic carbon (of ∼250 GtC). Its implementation in models needs to be better accounted for.



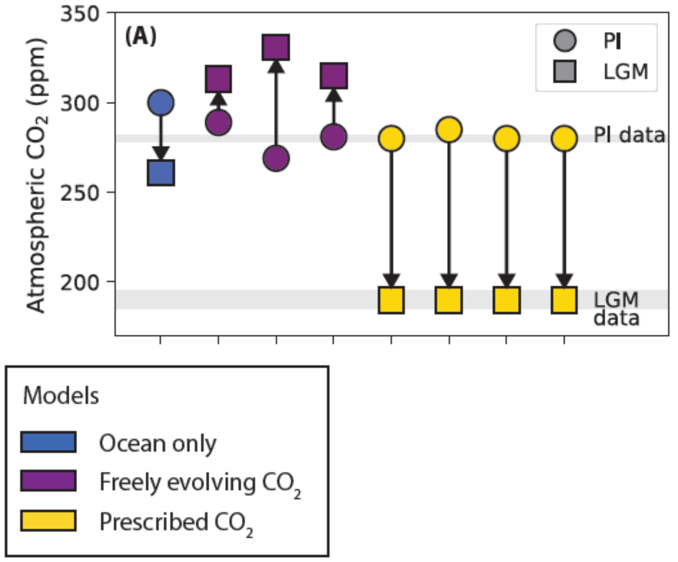


Figure 1. Winter sea-ice edge (at 15% of sea-ice concentration) in the Southern Ocean for the LGM simulations. The sea-ice presence suggested by marine core data is represented as an index on a blue to white scale: blue denotes no indication of sea ice, white denotes agreement of several proxies on the presence of sea ice. The red line marks the likely delimitation of sea-ice presence according to proxy data. From Lhardy et al. (2021a).
Figure 2. Atmospheric CO_2 concentration (ppm) obtained in the PMIP models. The grey lines indicate the pre-industrial (PI) and Last Glacial Maximum (LGM) data. From Bouttes et al. (2021).

Future of the project

We plan to further develop the iLOVECLIM model to account for all major carbon cycle reservoirs, to be able to understand and simulate the CO_2 change recorded for the LGM. For this we will add sediments, corals and permafrost.

Number of publications, communications and theses

7 Publications:

Lhardy, F. et al., Impact of Southern Ocean surface conditions on deep ocean circulation during the LGM: a model analysis, Clim. Past, 17, 1139–1159, https://doi.org/10.5194/cp-17-1139-2021, 2021a.

Lhardy, F. et al., A first intercomparison of the simulated LGM carbon results within PMIP-carbon: Role of the ocean boundary conditions. *Paleoceanography and Paleoclimatology*, 36, e2021PA004302, https://doi.org/10.1029/2021PA004302, 2021b.

Bouttes, N. et al., PMIP-carbon: A model intercomparison effort to better understand past carbon cycle changes, Past Global Changes Magazine, 29(2), 88-89, https://doi.org/10.22498/pages.29.2.88, 2021.

Kageyama, M. et al., The PMIP4 Last Glacial Maximum experiments: preliminary results and comparison with the PMIP3 simulations, Clim. Past, 17, 1065–1089, https://doi.org/10.5194/cp-17-1065-2021, 2021.

Civel-Mazens, M. et al., Impact of the Agulhas Return Current on the Kerguelen region, Southern Ocean, over the last glacial-interglacial cycle. *Quaternary Science Reviews*, 251, 106711 (doi: 10.1016/j.quascirev.2020.106711), 2021a.

Civel-Mazens, M. et al., Antarctic Polar Front migrations in the Kerguelen Plateau region, Southern Ocean, over the past 360 kyrs. *Global and Planetary Change*, 202, 103526 (doi: 10.1016/j.gloplacha.2021.103526), 2021b.

Bouttes, N. et al., Deglacial climate changes as forced by ice sheet reconstructions, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-993, 2022.

5 Communications:

- June 2019, CLIMERI, Bordeaux, poster
- July 2019, INQUA, Dublin, Ireland, oral
- February 2020, Q12, Paris, poster
- May 2020, EGU, poster (virtual)
- April 2021, EGU PICO (x2) (virtual)

1 PhD thesis: Fanny Lhardy, 27 September 2021: Role of Southern Ocean sea ice on deep ocean circulation and carbon cycle at the Last Glacial Maximum

Data availablility

The model outputs and reconstructed sea-ice limits: https://doi.org/10.5281/zenodo.4576026.
Model outputs of PMIP-carbon models and iLOVECLIM simulations: doi: 10.5281/zenodo.5464162.
Sea surface temperatures in core MD11-3353: https://doi.pangaea.de/10.1594/PANGAEA.930901