doi.org/10.22498/pages.29.2.88

PMIP-carbon: A model intercomparison effort to better understand past carbon cycle changes

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Past carbon cycle changes, especially during the Last Glacial Maximum 21,000 years ago, remain largely unexplained and difficult to simulate with numerical models. The ongoing PMIP-carbon project compares results from different models to improve our understanding of carbon cycle modeling.

PMIP-carbon

Atmospheric CO_2 concentration plays a major role for the Earth's climate as this is one of the main greenhouse gases. Moreover, the CO_2 level directly influences the ocean pH with large impacts on marine biology. Hence, understanding the carbon cycle, and its past changes, is critical. The carbon cycle at short timescales corresponds to the exchange of carbon between the main carbon reservoirs: ocean, atmosphere, terrestrial biosphere, surface sediments, and permafrost (Fig. 1). The atmospheric CO_2 concentration depends on the carbon fluxes and how much carbon is stored in the various reservoirs.

We know from proxy data that the atmospheric CO_2 level has varied largely in the past. In particular, measurements of CO_2 concentration in air bubbles trapped in ice cores indicate lower values of ~190 ppm during cold glacial periods compared to values of ~280 ppm during warmer interglacial periods (Bereiter et al. 2015 and references therein). Many studies have focused on explaining the low CO_2 during the Last Glacial Maximum (LGM), but no consensus on the main mechanisms has been reached yet. Most models do not simulate such a low value, especially when they are simultaneously constrained by other proxy data such as carbon isotope values.

Nonetheless, several potential mechanisms have emerged (Bouttes et al. 2021). Firstly, the ocean is assumed to play a major role; this is the largest reservoir relevant for these timescales, meaning that any small change in its carbon storage could result in large modifications in the atmospheric CO_2 concentration. In addition, proxy data, such as carbon isotopes, seem to indicate changes in ocean dynamics and/or biological production. Besides the ocean, the sediment and permafrost reservoirs have also expanded during the LGM, helping to decrease atmospheric CO_2. Conversely, the terrestrial biosphere lost carbon at the LGM, indicating that even more carbon was taken up by the other reservoirs.

Until now, the different working groups within PMIP have mainly focused on climate without considering carbon cycle changes. A new project was recently defined as part of the deglacial working group in PMIP4 to tackle the issue of past carbon cycle changes. The objectives of this model intercomparison are to evaluate model responses in order to better understand the changes, help find the major mechanisms responsible for the carbon cycle changes, and improve models. As a starting point, the project focuses on the LGM, hence the protocol follows the main LGM PMIP4 guidelines for greenhouse gases, insolation, and ice sheets, as closely as possible (Kageyama et al. 2017). The same numerical code should be used for the pre-industrial period and the LGM, including the carbon cycle modules.

First results: Carbon storage changes in the main three reservoirs

So far, three GCMs (MIROC-ES2L, CESM and IPSL-CM5A2), four EMICs (CLIMBER-2, iLOVECLIM, MIROC-ES2L, LOVECLIM, UVic), and one ocean only GCM (MIROC4m) have been participating in PMIP-carbon. As not all models have all carbon cycle components (particularly sediments and permafrost), this first intercomparison exercise is focused on simulations with the ocean, terrestrial biosphere, and atmosphere carbon reservoirs only.

It should be noted that there are often two CO_2 variables in models: one for the radiative code–generally fixed to a prescribed value to ensure a correct climate–and another one for the carbon cycle. The latter can be prescribed to the same values as the CO_2 for the radiative code (yellow in Fig. 2a) or can be allowed to evolve freely in the carbon cycle model based on the fluxes with the other carbon reservoirs (purple and blue in Fig. 2a).

The most striking result is that in models that do not prescribe atmospheric CO_2 and

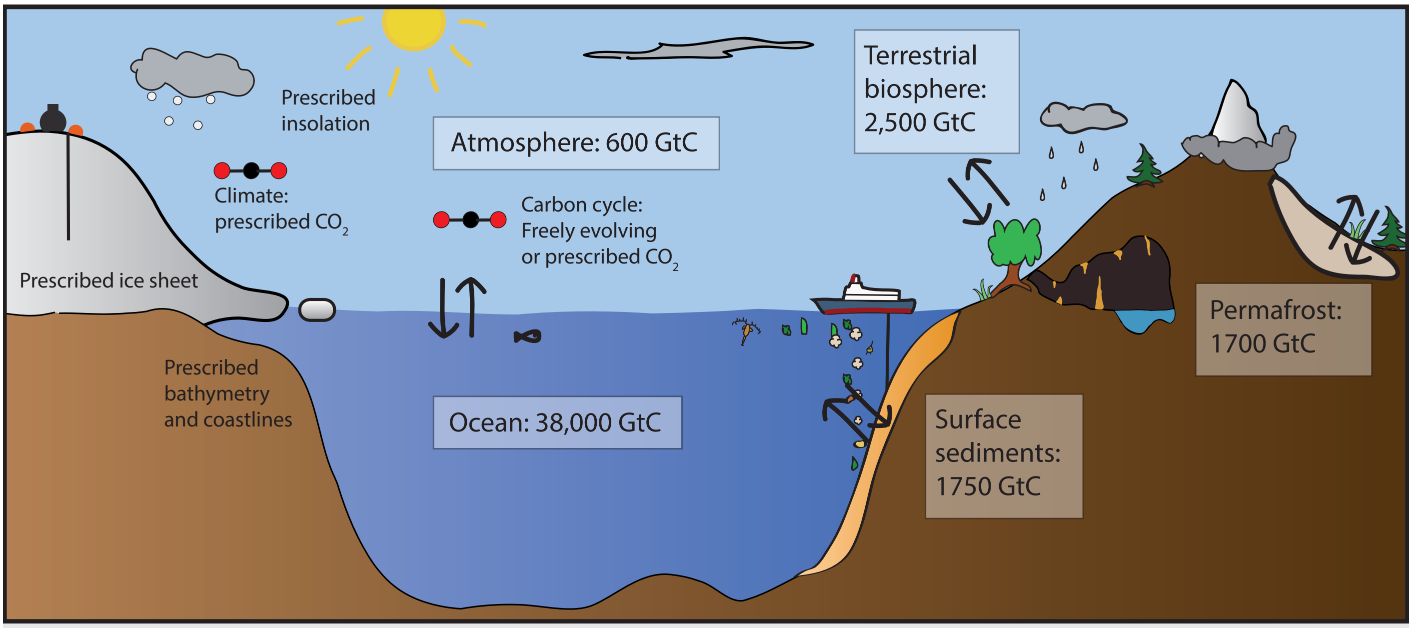

Figure 1: Schematic of the short-term carbon cycle with the main reservoirs and their estimated carbon content at the pre-industrial. The long-term processes (longer than 100 kyr) such as volcanism or silicate weathering are not considered. Also indicated are the boundary conditions imposed in climate models and the two types of simulation of atmospheric CO_2.

include the terrestrial biosphere (purple in Fig. 2a), the LGM CO_2 concentration is higher than during the pre-industrial, rather than lower, as indicated by the data. In the ocean-only model (blue in Fig. 2a), the CO_2 is lower at the LGM, but the amplitude is very small compared to the data.

In agreement with data reconstructions, the land carbon storage (vegetation and soils) decreases from the pre-industrial to the LGM (Fig. 2b) due to the colder LGM climate and larger ice sheets. The amplitude of this decrease varies between models, possibly due to differences in the terrestrial biosphere modules, and differences in the simulated climate (Kageyama et al. 2021). However, this could also result from different prescribed boundary conditions, such as coastlines and ice-sheet extents, both of which yield different land surfaces at the LGM and, hence, more or less space for vegetation to grow.

In the ocean, model results are more variable. Most models with prescribed atmospheric CO_2 (except LOVECLIM) indicate a loss of ocean carbon storage, at odds with the general view of increased carbon storage. In the models with freely evolving CO_2, the ocean stores more carbon (a similar result is seen in LOVECLIM simulations), but this effect is far too small to counteract the loss of carbon from land. This, therefore, results in atmospheric CO_2 values far outside of the range of the data.

The carbon storage in the ocean is the result of many competing processes. For example, on the one hand, lower temperatures increase CO_2 solubility, and increased nutrient concentrations due to lower sea level (of ~130 m) yields more productivity, both lowering atmospheric CO_2. On the other hand, the increased salinity due to sea-level change tends to increase atmospheric CO_2. While these mechanisms are relatively well understood, the change of ocean circulation is still a major issue in models (Kageyama et al. 2021). PMIP-carbon aims to understand these model differences and highlight missing processes in the ocean.

One result that has already emerged is the importance of the ocean volume: at the LGM the ocean volume was reduced by ~3% due to the sea-level drop, yielding a reduced ocean carbon reservoir size (Lhardy et al. 2021). This means that the ocean (by means of other processes), sediments, and permafrost have to store even more carbon to counteract this effect. For modeling groups, it also means that accounting for realistic bathymetry and coastline changes is essential; at the very least, the changes of oceanic variable concentrations such as alkalinity in models must be treated with great care.

Looking forward

In the short-term, PMIP-carbon will aim for more in-depth analyses of the ocean and terrestrial biosphere to understand the differences between models using existing (and ongoing) simulations.

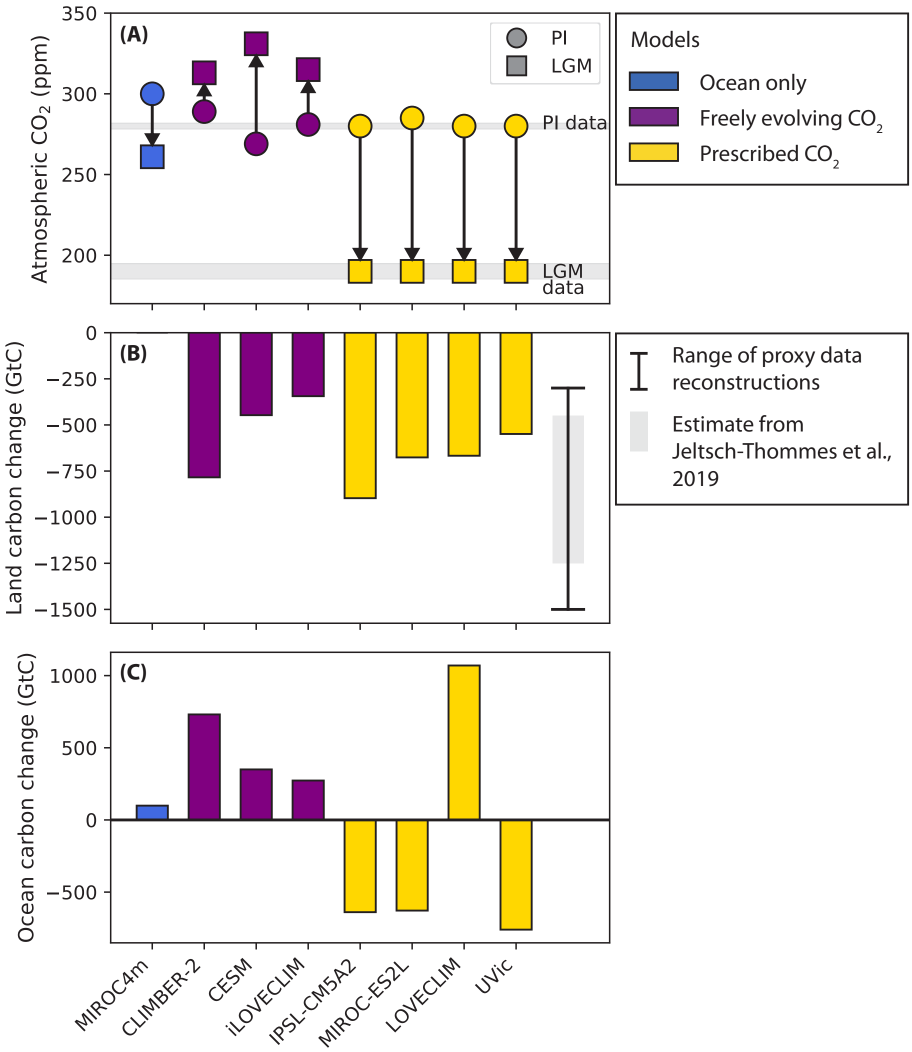

Figure 2: Carbon in three reservoirs: **(A)** Atmospheric CO_2 concentration (ppm), **(B)** terrestrial biosphere carbon change from PI to LGM (GtC) and **(C)** ocean carbon change (GtC). CO_2 data from Bereiter et al. (2015). Reconstruction of terrestrial biosphere carbon change using proxy data ranging from 300 GtC with carbon isotopes to 1500 GtC from pollen records (see Jeltsch-Thommes et al. 2019 for a more in-depth discussion).

However, the atmospheric CO_2 change that has to be explained is actually more than just the observed 90 ppm fall. Several changes tend to increase the CO_2 concentration, such as the loss of terrestrial biosphere, or the reduced ocean volume due to lower sea level. Hence, in addition to oceanic processes, other carbon reservoirs, such as sediments and permafrost, will be essential to explain the lower atmospheric CO_2. In the future, these additional components will be added to the protocol and their effects will be compared between models.

Finally, even if the LGM is an interesting period to study, the long-term objective of PMIP-carbon is to also compare model results during other periods such as the last deglaciation for which more challenges will arise: on top of the large glacial-interglacial 90 ppm change, the transition shows rapid changes in the carbon cycle which are not yet well understood (Marcott et al. 2014).

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