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Carbon isotope modeling implications for changes in the Southern Ocean carbon cycle during the last deglaciation

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Atmospheric carbon dioxide (pCO_2) concentrations increased by about 80 ppm from the Last Glacial Maximum (LGM) to the early Holocene, reflecting the climate system's response to gradual changes in insolation. Previous models have suggested that this deglacial pCO_2 increase was mainly due to CO_2 released from the ocean, partly influenced by abrupt shifts in the Atlantic Meridional Overturning Circulation (AMOC) and associated interhemispheric climate changes. However, a comprehensive understanding of how changes in ocean circulation and geochemical properties during the last deglaciation influenced atmospheric pCO_2 remains elusive.

This study narrows the focus to the Southern Ocean and examines its role in changes in the ocean carbon cycle during the last deglaciation (21 to 11 ka BP) using three-dimensional ocean fields from the MIROC 4m climate model, which successfully simulates abrupt AMOC shifts seen in reconstructions. We aim to improve our understanding by comparing modeled carbon isotope ratios with sediment core data, identifying model biases and highlighting potentially underestimated processes.

The simulation is in qualitative agreement with ice core records of atmospheric pCO_2 fluctuations: an increase of 10.2 ppm during the Heinrich Stadial 1 (HS1), a decrease of 7.0 ppm during the Bølling-Allerød, and a subsequent increase of 6.8 ppm during the Younger Dryas. Nevertheless, the model underestimates pCO_2 changes compared to ice core data, suggesting that some ocean dynamics have been missed in the simulations.

A particular limitation of the model is its underestimation of the influence of the Southern Ocean, especially during HS1. This suggests a misrepresentation of the complex interplay between activated deep ocean ventilation, reduced biological carbon export efficiency, and their cumulative effect on atmospheric pCO_2.

The decomposition of the drivers of ocean pCO_2 changes highlights temperature and alkalinity as key drivers. Their interaction reveals the intricate link between AMOC shifts, Southern Ocean carbon dynamics leading to changes in SST and geochemical properties, and the resulting atmospheric pCO_2 variations during deglaciation. This study underscores the critical need for detailed modeling of Southern Ocean biogeochemical processes to refine our understanding of past and future climate dynamics.