論文の内容の要旨

Role of ocean carbon cycle in glacial reduction of atmospheric carbon dioxide concentration

(氷期の大気中二酸化炭素濃度低下における海洋炭素循環の役割)

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From climate reconstructions using ice core records, it is shown that atmospheric carbon dioxide concentration (pCO_2) at the Last Glacial Maximum (LGM) is about 100 ppm lower than that at the pre-industrial period. Since carbon isotope data from ocean sediment records indicates that carbon storage in the terrestrial biosphere was reduced at the LGM, this atmospheric pCO_2 reduction must have arose from changes in the ocean carbon cycle. Paleo-ocean reconstructions recently show that high-salinity and old water mass occupied the deep Southern Ocean at the LGM. These reconstructions suggest a hypothesis that carbon storage in the deep Southern Ocean increased at the LGM as a result of enhanced salinity stratification and caused a decline in atmospheric pCO_2 ("Southern Ocean hypothesis"). However, previous studies using an ocean general circulation model (OGCM) underestimate the pCO_2 change between the LGM and pre-industrial. One of the causes of this underestimation in OGCM studies is that the enhanced stratification in the glacial Southern Ocean suggested by the Southern Ocean hypothesis may not be appropriately represented by

OGCMs. In this study, I focus on the Southern Ocean hypothesis and attempt to explain the mechanism of ocean carbon cycle change which contributes to the 100-ppm decline of atmospheric pCO_2 at the LGM.

In Chapter 2, I first try to improve the insufficient reproducibility of the high-salinity and old water mass in the glacial deep Southern Ocean, and then investigate its influence on the ocean carbon cycle and atmospheric pCO_2. For this purpose, a LGM simulation is conducted, in which salinity in the ocean deepest layer in the Southern Ocean is restored toward high salinity reported from paleo-ocean proxy data and small vertical diffusion coefficient is prescribed to reproduce the enhanced stratification in the Southern Ocean. In the simulated glacial Southern Ocean, salinity stratification is strengthened, and the residence time of deep water gets longer. As a consequence, the concentration of dissolved inorganic carbon (DIC) increases in the Southern Ocean and decreases in the surface ocean through ocean biological process, which lowers atmospheric pCO_2. However, the glacial decline in atmospheric pCO_2 is only about 47 ppm.

In Chapter 3, in addition to results of OGCM simulations reported in Chapter 2, the role of carbonate compensation process in the glacial reduction of atmospheric pCO_2 is investigated with a newly created ocean sediment model. As a result of carbonate compensation, atmospheric pCO_2 decreases due to an increase in whole ocean alkalinity as previous studies suggested. It is newly found that this carbonate compensation process works more effectively by the enhanced stratification in the Southern Ocean. Owing to this contribution, the glacial reduction of atmospheric pCO_2 reaches about 73 ppm, which is much larger response than that obtained in previous OGCM studies.

In Chapter 4, I attempt to reproduce the physical ocean fields at the LGM by introducing parameterizations of brine rejection during sea ice production and stratification-dependent vertical diffusion coefficient. By using the brine parameterization, I confirm that the high bottom-water salinity in the glacial Southern Ocean obtained in Chapter 2 and 3 is similarly reproduced. Furthermore, when the parameterization of stratification-dependent vertical diffusion coefficient is introduced to the LGM simulation, it results in a more pronounced increase in the vertical gradient of DIC compared with the case of Chapter 2 and 3 in which the vertical diffusion coefficient is reduced only in the Southern Ocean. As a consequence, the difference in atmospheric pCO_2 between the LGM and pre-industrial simulation becomes larger than 90 ppm; therefore, in this study, most of the glacial atmospheric pCO_2 reduction reported from ice core records can be successfully explained under the constraints of paleo-ocean reconstructions.

This study quantitatively demonstrates that changes in the ocean carbon cycle due to the enhanced salinity stratification in the glacial Southern Ocean and carbonate compensation process are essential for explaining the glacial reduction of atmospheric pCO_2 by about 100 ppm.