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Response of atmospheric pCO_2 to glacial changes in the Southern Ocean amplified by carbonate compensation

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Atmospheric carbon dioxide concentration (pCO_2) varies by about $100\,\mathrm{ppm}$ during glacial-interglacial cycles. Previous studies suggest that the strongly stratified Southern Ocean at the Last Glacial Maximum increases the oceanic storage of carbon, but the glacial reduction of atmospheric pCO_2 simulated by ocean general circulation models (OGCMs) does not reach $100\,\mathrm{ppm}$. One candidate for the underestimation is that carbonate compensation is not explicitly incorporated in the previous OGCM simulations. Therefore, we quantitatively evaluate the impact of carbonate compensation on the glacial atmospheric pCO_2 by using an OGCM coupled with an ocean sediment model. As suggested by previous box model studies, our OGCM simulations show that the enhanced Southern Ocean stratification amplifies the decrease in atmospheric pCO_2 due to carbonate compensation. Considering the enhanced stratification in the Southern Ocean, we obtain a $26\text{-}\mathrm{ppm}$ drawdown of atmospheric pCO_2 by carbonate compensation, and the full reduction from our pre-industrial simulation reaches $73\,\mathrm{ppm}$. Both the increase in ventilation ages in the deep Atlantic and Southern Oceans, which arises from the weakening of Atlantic meridional overturning circulation and the suppression of open-ocean deep convection, and the growth of export production in the subantarctic region reduce the bottom-water carbonate ion and promote deposited carbonate dissolution. Consequently, a greater imbalance between the river inflow and burial loss of carbonate rises ocean alkalinity, lowering atmospheric pCO_2. We suggest that the reproducibility of the Southern Ocean process is essential for controlling the magnitude of atmospheric pCO_2 decline due to carbonate compensation.