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A process-based understanding of the late Cenozoic carbon cycle

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On a million-year time scale the global carbon cycle and atmospheric CO_2 are assumed to be largely determined by the so-called solid Earth processes weathering, sedimentation, and volcanic outgassing. However, it is not clear how much of the observed dynamics in the proxy data constraining the carbon cycle over the Cenozoic might be determined by internal processes of the atmosphere-ocean-biosphere subsystem. Here, we apply for the first time a process-based model of the global carbon cycle in transient simulations over the last 20 Myr to identify the contributions of terrestrial carbon storage, solubility pump and ocean gateways on changes in atmospheric CO_2 and marine δ^{13}C. We apply the isotopic carbon cycle box model BICYCLE, which consists of atmosphere, terrestrial biosphere and ocean reservoirs, the latter containing the full marine carbonate system. Our simulation results show that the long-term cooling since the Mid Miocene Climatic Optimum (about 15 Myr BP) leads to an intensification of the solubility pump, and a drop in atmospheric CO_2 of up to 100 ppmv. This oceanic carbon uptake is largely counterbalanced by carbon loss from the terrestrial biosphere. The reduction in terrestrial C storage over time including the expansion of C4 grasses during the last 8 Myr might explain half of the long-term decline in deep ocean δ^{13}C and would support high CO_2 (400 to 450 ppmv) around 15 Myr BP. The closure of the Tethys and the Central America ocean gateways explains the developing gradient in deep ocean δ^{13}C between the Atlantic and Pacific basin. We furthermore calculate the residuals, which are unexplained by our results and are therefore caused by solid Earth processes. From the residuals ocean alkalinity rising over time is detected as the main reason for declining atmospheric CO_2 which led to Earth's long-term cooling observed since the Mid Miocene Climate Optimum. A combination of two processes — a reduction in volcanic out-gassing of CO_2 together with increasing continental weathering rates — might explain the rising alkalinity pattern. The reduced volcanic activity probably caused by shrinking seafloor spreading rates started around 16 Myr BP is connected with a prominent regime shift in the carbon cycle-climate system. The existence of such a regime shift is confirmed if we extend our analysis to deep ocean records of δ^{18}O and δ^{13}C over the whole Cenozoic.