Multi-centennial variability of the Atlantic Meridional Overturning Circulation: underlying mechanisms and its response to elevated CO$_2$ levels

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Multi-centennial climate variability, evident in paleoclimate proxy records and observed in both forced transient and unforced control simulations with numerous fully coupled climate models, presents a significant yet elusive phenomenon in climate dynamics. This study, utilizing a coupled climate model EC-Earth3-LR, identifies and analyzes a prominent multi-centennial climate variability with a distinct 200-year cycle in a pre-industrial (PI, with atmospheric CO$_2$ concentration of 280 ppmv) control simulation. This oscillation originates predominately from the North Atlantic and displays a strong association with the Atlantic Meridional Overturning Circulation (AMOC).

We pinpoint the crucial interplay between salinity advection feedback and vertical mixing in the subpolar North Atlantic as key roles in providing the continuous internal energy source to maintain this multi-centennial oscillation. The perturbation flow of mean subtropical-subpolar salinity gradients serves as positive feedback that sustain the AMOC anomaly, while the mean advection of salinity anomalies and the vertical mixing acts as negative feedback, constraining the amplitude of AMOC anomaly.

In warmer climate conditions, with atmospheric CO$_2$ concentrations elevated to 400 ppmv and 560 ppmv, we observe an expected stabilization of the water column in the North Atlantic deep-water formation regions, potentially leading to a reduction in the AMOC. These conditions are simulated to assess the evolution of unforced internal multi-centennial variability under higher CO$_2$ levels. Results show that while multi-centennial climate variability persists in these warmer climate states, oscillation amplitudes are diminished. Despite the reduced intensity, the most pronounced effects remains in the North Atlantic and the Arctic, hypothesized to be driven by AMOC fluctuations. In contrast to the PI simulation, where the Arctic and subtropical fluxes exhibit aligned power spectra peaks, the warmer climate scenarios reveal longer timescales and reduced amplitudes in multi-centennial climate variability, suggesting a climate state dependence in the subtropical mechanism. Notably, while the subtropical salinity feedback is coupled with the Arctic mechanism in the PI state, it evolves into a weaker, slower, and self-sustaining mechanism in warmer climates.