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Changes in deep-water formation amplify the Earth's Equilibrium Climate Sensitivity on multi-centennial time scales

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Quantifying the Earth's climate system response to changes in atmospheric carbon dioxide (CO_2) concentrations is crucial for understanding the impact of greenhouse gases on the Earth's past, present, and future climate. The sensitivity of the Earth's climate to increasing CO_2 levels will largely determine the environmental conditions faced by human societies, fauna, and flora in the years to come. Projected future climate conditions depend on the sensitivity of the numerical models employed. Therefore, a comprehensive understanding of model sensitivity to radiative forcing across various temporal and spatial scales is essential. Towards this goal, we employ the newly developed AWI-CM3 model, which will be used for future climate projections in CMIP7, to examine Equilibrium Climate Sensitivity (ECS) across different time scales.

Our quasi-equilibrium simulations span 2,000 model years, subjected to atmospheric CO_2 concentrations of 280, 400, 560, and 1120 ppmv. The highest concentration simulation is inspired by the CMIP6 *abrupt4xCO2* protocol, designed to assess climate response to an abrupt change in radiative forcing. Notably, our simulations run much longer than the CMIP6 suggested 150-year duration. The lower concentration simulation represents the pre-industrial period (PI), while the remaining were designed to investigate the climate with CO_2 concentrations similar to the current climate and with a doubling of PI levels, respectively.

The ECS derived from AWI-CM3 stands at 3.95ºC, ranking it as medium-range sensitivity compared to the CMIP6 ensemble. A key finding is that ECS increases by up to 1.5ºC when simulations are extended beyond the CMIP6 minimum runtime requirement. This change in ECS correlates to alternations in deep water formation in both the North Atlantic and Southern Oceans. Throughout the simulations, we note adjustment processes in the overall climate and multi-centennial variability in the strength of the Atlantic Meridional Overturning Circulation (AMOC) due to changes in North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) formation.

The simulations also reveal a progressive weakening and shallowing of the AMOC and a strengthening of the AABW as CO_2 concentrations increase. Beyond 200 years, under adjusted radiative forcing, the AMOC recovers, but the resultant circulation pattern features persistently shallower NADW and a weaker, more northward-extending AABW in the Atlantic and Pacific

Oceans. Our results highlight the intricate relationship between deep water formation and Earth's equilibrium climate sensitivity. Furthermore, our findings suggest a need to reevaluate the current framework for deriving ECS in the standard CMIP6 methodology. Prolonged simulations not only enhance our understanding of the underlying mechanisms driving climate sensitivity to changing radiative forcing but also provide valuable insights into the time required for the Earth's climate to adjust to these changes.