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Reversibility in an Earth System model in response to CO_2 concentration changes

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There is considerable uncertainty in future emission and concentration pathways of greenhouse gases. Mitigation scenarios aiming to avoid potentially dangerous climate change are likely to require significant reductions in greenhouse gas emissions within the next two decades. However, it is conceivable that early CO_2 emissions reduction may not be achieved and the current rapid growth in greenhouse gas concentrations may continue for at least several decades. This creates an urgent need to understand whether the undesirable elements of climate change that occur during the global warming period can be reversed in a usefully short time if ever it becomes possible in the future to lower the atmospheric concentration of greenhouse gases through economically viable CO_2 air capture, possibly associated with a rapid decarbonisation of the economy. We use here the HadGEM2-ES Earth System model to examine the degree of reversibility of a wide range of components of the Earth System under idealised climate change scenarios where the atmospheric CO_2 concentration is gradually increased to four times the preindustrial level and then reduced at a similar rate from several points along this trajectory. While some modelled quantities respond almost immediately to the atmospheric CO_2 concentrations, others exhibit a time lag relative to the change in CO_2. Most quantities also exhibit a lag relative to the global-mean surface temperature change, which can be described as a hysteresis behaviour. The most surprising responses are from low-level clouds and ocean stratification in the Southern Ocean, which both exhibit hysteresis on timescales longer than expected. We see no evidence of critical thresholds in these simulations, although some of the hysteresis phenomena become more apparent above 2xCO_2 or 3xCO_2. Our findings have implications for the parametrization of climate impacts in integrated assessment and simple climate models and future climate studies of geoengineering scenarios.