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# Concurrent Miocene Antarctic ice sheet growth and CO2 increase caused by disequilibrium

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Geological evidence indicates considerable Antarctic ice volume variations during the early to mid-Miocene. Hitherto, ice modelling studies have mostly used equilibrium simulations to explain this variability. In these simulations, the gain in precipitation due to increased temperatures has to outweigh the loss caused by increased ice melt, to obtain simultaneous ice sheet growth and $CO_2$ level rise. Here, conceptualising ice dynamical model results, we find that this is not a necessary condition for the transiently evolving Miocene Antarctic ice sheet. Instead, ice volume increase when $CO_2$ levels are rising can also be explained as a consequence of disequilibrium between the transiently changing ice volume and forcing climate. This disequilibrium permits a continuation of ice sheet growth after a gradual $CO_2$ decline. When the $CO_2$ level is increased again, the ice sheet is still adapting to a relatively large equilibrium volume. Lowering the periodicity of the forcing leads to a larger disequilibrium, and consequently larger $CO_2$-ice volume phase differences. Furthermore, amplified forcing variability increases ice volume variations, because the growth and decay rates depend on the forcing. It also leads to a reduced average ice volume, which is induced by the growth rate generally being smaller than the decay rate. We therefore submit that retrieval of high resolution proxy-$CO_2$ records covering the Miocene would be very beneficial to constrain ice modelling studies.