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# An empirical response function for the long-term fate of excess atmospheric $CO_2$

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The long-term fate of fossil fuel $CO_2$ emitted to the atmosphere is neutralization by a number of sedimentological and geological processes operating on timescales ranging from thousands to hundreds of thousands of years. However, the response of these carbon cycle processes to increasing total emissions is not known, such as whether saturation of the long-term $CO_2$ sinks might occur or a weakening of the associated feedbacks. This could have important implications for components of the Earth system that are slow to respond to changes in temperature, such as ice sheets and methane hydrates. Here we use a 3D ocean-based Earth system model to assess the relative importance and timescales of these processes for different total emissions. A multi-exponential analysis is performed on an ensemble of 1 Myr duration $CO_2$ decay curves spanning cumulative emissions of up to 20,000 PgC, generating an empirical response function characterizing the long-term (> 1 kyr) fate of $CO_2$. For a realistic time-dependent carbon release, a simple pulse-response description results in large predictive errors early on in the simulation. As a result, we develop a convolution-based description of atmospheric $CO_2$ decay which significantly decreases these initial residuals. Our response function represents a simple and practical tool for rapidly projecting the atmospheric lifetime of a wide range of $CO_2$ emission sizes, and in convolution form, can be used across a large range of rates of release, allowing it to be used in place of more complex models for assessing the long-term atmospheric $CO_2$ perturbation following future anthropogenic emissions. Our analysis also reveals that, as the marine $CO_2$ sinks become saturated, both the fraction of total emissions that are removed from the atmosphere via carbonate weathering and burial and the timescale of removal progressively increase. However, we find that the ultimate $CO_2$ sink – silicate weathering feedback – is approximately invariant with respect to cumulative emissions, both in terms of its importance ($\sim$7%) and timescale ($\sim$265 kyr).