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The Transient Response of the Carbon-Cycle-Climate Continuum to CO_2 Emissions is Pathway Dependent

Alexander J. Winkler[1,2], Ranga B. Myneni[3], Markus Reichstein[1], and Victor Brovkin[2]
[1]Max-Planck-Institute for Biogeochemistry, Jena, Germany (awinkler@bgc-jena.mpg.de)
[2]Max-Planck-Institute for Meteorology, Hamburg, Germany
[3]Department of Earth and Environment, Boston University, United States of America

The prevailing understanding of the carbon-cycle response to anthropogenic CO_2 emissions suggests that it depends only on the magnitude of this forcing, not on its timing. However, a recent study (Winkler *et al*., *Earth System Dynamics*, 2019) demonstrated that the same magnitude of CO_2 forcing causes considerably different responses in various Earth system models when realized following different temporal trajectories. Because the modeling community focuses on concentration-driven runs that do not represent a fully-coupled carbon-cycle-climate continuum, and the experimental setups are mainly limited to exponential forcing timelines, the effect of different temporal trajectories of CO_2 emissions in the system is under-explored. Together, this could lead to an incomplete notion of the carbon-cycle response to anthropogenic CO_2 emissions.

We use the latest CMIP6 version of the Max-Planck-Institute Earth System Model (MPI-ESM1.2) with a fully-coupled carbon cycle to investigate the effect of emission timing in form of four drastically different pathways. All pathways emit an identical total of 1200 Pg C over 200 years, which is about the IPCC estimate to stay below 2 °K of warming, and the approximate amount needed to double the atmospheric CO_2 concentration. The four pathways differ only in their CO_2 emission rates, which include a constant, a negative parabolic (ramp-up/ramp-down), a linearly decreasing, and an exponentially increasing emission trajectory. These experiments are idealized, but designed not to exceed the observed maximum emission rates, and thus can be placed in the context of the observed system.

We find that the resulting atmospheric CO_2 concentration, after all the carbon has been emitted, can vary as much as 100 ppm between the different pathways. The simulations show that for pathways, where the system is exposed to higher rates of CO_2 emissions early in the forcing timeline, there is considerably less excess CO_2 in the atmosphere at the end. These pathways also show an airborne fraction approaching zero in the final decades of the simulation. At this point, the carbon sinks have reached a strength that removes more carbon from the atmosphere than is emitted. In contrast, the exponentially increasing pathway with high CO_2 emission rates in the last decades of the simulation, the pathway usually studied, shows a fairly stable airborne fraction. We propose a new general framework to estimate the atmospheric growth rate of CO_2 not only as a function of the emission rate, but also include the aspect of time the system has been exposed to excess CO_2 in the atmosphere. As a result, the transient temperature response is a function not only of the cumulative CO_2 emissions, but also of the time the system was exposed to the excess CO_2. We also apply this framework to other Earth system models and observational records of CO_2 concentration and emissions.

The Earth system is currently in a phase of increasing, nearly exponential CO_2 forcing. The impact of excess CO_2 exposure time could become apparent as we approach the point of maximum CO_2 emission rate, affecting the achievability of the climate targets.