Much of Zero Emissions Commitment Occurs Before Reaching Net Zero Emissions

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Abstract

We explore the response of the Earth’s climate and carbon system to an idealized sequential addition and removal of CO$_2$ to the atmosphere, following a symmetric and continuous emissions pathway, in contrast to the discontinuous emissions pathways that have largely informed our understanding of the climate response to net-zero and net-negative emissions to date. We find, using both an Earth System Model and an ensemble of simple climate model realizations, that warming during the emissions reduction and negative emissions phases is defined by a combination of a proportionality of warming to cumulative emissions characterized by the transient climate response to emissions (TCRE), and a deviation from that proportionality that is governed by the zero emissions commitment (ZEC). About half of the ZEC is realized before reaching zero emissions, and the ZEC thus also controls the timing between peak cumulative CO$_2$ emissions and peak temperature, such that peak temperature may occur before peak cumulative emissions if ZEC is negative, underscoring the importance of ZEC in climate policies aimed to limit peak warming. Thus we argue that ZEC is best defined as the committed warming relative to the expected TCRE proportionality, rather than the additional committed warming that will occur after reaching net zero CO$_2$ emissions. Once established, the combined TCRE and ZEC relationship holds almost to complete removal of prior cumulative CO$_2$ emissions. As cumulative CO$_2$ emissions approach zero through negative CO$_2$ emissions, CO$_2$ concentrations drop below preindustrial values, while residual long-term climate change continues, governed by multicentennial dynamical processes.

Significance Statement

We use climate models to explore both the amount of global warming and the relative timing between warming and carbon dioxide emissions, under an idealized scenario where carbon dioxide emissions gradually cease and then reverse, such that the timing and amount of carbon dioxide removals is exactly the reverse of prior emissions. We find that a metric of long-term committed warming begins to occur soon after emission rates peak, and controls the timing of when temperatures begin to cool relative to when net-zero carbon dioxide emissions occur. Overall, we find that global warming is proportional to cumulative carbon dioxide emissions plus the committed warming metric as we start to reduce and eventually reverse emissions.
Introduction

Current climate policy is predicated on the idea that the magnitude of global warming is proportional to cumulative emissions of carbon dioxide (1, 2). This relationship emerges from complex interactions between the physical and biogeochemical aspects of the Earth system, and has been consistent across all coupled carbon-climate models under scenarios of positive CO₂ emissions (3, 4). The simplicity and path independence of the relationship allow the creation of a remaining carbon budget consistent with a specific warming level. However, the path independence of the relationship between warming and cumulative CO₂ emissions, known as the Transient Climate Response to Emissions (TCRE), is only approximate – for example it is possible that some remaining CO₂-driven temperature change will occur even after emissions cease, and this deviation from the path independence of the TCRE approximation can be quantified as the Zero Emission Commitment (ZEC) (5–7), which is used alongside the TCRE in constructing a remaining carbon budget for climate stabilization for policy applications (8).

The modeled proportionality of warming to cumulative emissions, despite emerging from complex and at least partially coincidental interactions (9–11), holds to a remarkably high amount of cumulative emissions (12, 13). Likewise, under negative CO₂ emissions, the proportionality of warming to cumulative CO₂ emissions still holds as cumulative emissions decrease, subject to an asymmetry that is governed by the ZEC (13) in both idealized (14) and scenario-driven (13) experiments for overshoots up to ~300 Pg C. Thus, a hypothetical framework for highly mitigated scenarios, that long-term warming equals the sum of cumulative emissions times TCRE plus a committed ZEC value, may hold from net zero to net negative emissions. While the expected time lag between CO₂ emissions and CO₂-driven warming is only about a decade (15), the controls of that lag remain insufficiently quantified. The idealized experiments used to quantify TCRE and ZEC, where TCRE is the warming during the exponential CO₂ concentration growth phase (16) and ZEC is the subsequent warming after emissions instantaneously go to zero (17) do not allow assessment of when ZEC may occur as emissions decrease on the path to net zero or net negative CO₂ emissions.

It is also not clear how far the relationship between warming, cumulative emissions and ZEC described above would hold under negative emissions. Thus, here we ask whether temperature remains proportional to cumulative emissions, plus a ZEC value, as far as to the net removal of all anthropogenic CO₂ emissions in pursuit of restoration of the climate system to a preindustrial-like state, which we term a restoration scenario. Previous work on the reversibility of climate change under declining CO₂ has used time-reversed CO₂ concentration scenarios, with either idealized (18–21) or scenario-driven (22, 23) experiments. These experiments are critical in showing asymmetries in the climate and carbon cycle with respect to changing CO₂ concentrations, e.g., that there is a substantial lag between global temperature change and CO₂ concentrations after the transition from positive to negative emissions(24). While, in general,
concentration-driven experiments can be used to infer emissions and thus frame climate outcomes in terms of compatible emissions, the abrupt reversal from increasing to declining CO\textsubscript{2} concentrations in these scenarios requires a highly discontinuous emissions timeseries, instantly changing \textasciitilde50 Pg C/yr from large positive to large negative values (fig. S1a). Because the inertia of the Earth system acts like a low-pass filter, it is possible that this abrupt and very large change in emissions, which also holds for pulse CO\textsubscript{2} emission or removal experiments (15, 25), pushes the path independence of the TCRE to the point where it may no longer hold on shorter timescales. For example, in idealized 1%/yr reversal experiments, the proportionality of warming to cumulative emissions does not generally hold, as global temperatures are warmer for a given level of emission during the negative emissions period than during the positive emissions period(19), which we also find for the CMIP6 CDRMIP ensemble mean (fig. S1b). In scenario-based overshoot projections, the transition from positive to negative emissions takes decades (fig. S2), thus such large abrupt transitions in emissions are unlikely to occur.

We thus design and perform an idealized emission-driven carbon dioxide removal (CDR) experiment with the following three goals: we seek first to avoid sharp discontinuities in emissions, so as not to break the path-independence of the TCRE relationship or the timing of ZEC emergence due to any such discontinuities, second to have roughly exponential ramp-up of emissions early in the scenario to match the shape of historical emissions, and third to keep emissions symmetric in time before and after net zero to explore asymmetries in carbon fluxes and climate responses with respect to emissions. A simple experimental design that satisfies all of these criteria is to let cumulative CO\textsubscript{2} emissions follow a Gaussian curve in time, and thus let annual emissions follow the first derivative of a Gaussian. We force both the Community Earth System Model, version 2 (CESM2) (26) and a simple climate model FaIR 1.3 (27, 28) under such a scenario, with cumulative emissions reaching a maximum of 1000 Pg C after 150 years of simulation, and returning to zero after 300 years (figs 1a-b). This climate restoration experiment then allows us to ask several related questions: (1) how would the Earth system respond to the removal of all previously-emitted CO\textsubscript{2}, (2) what are the lags and asymmetries of the transient response of climate and carbon cycle dynamics to a symmetric shift from positive to negative CO\textsubscript{2} emissions around the point of the emissions reversal, and (3) how does the ZEC impact the relative timing between peak cumulative emission and peak warming?

**Results**

Carbon fluxes between the atmosphere and both the terrestrial and ocean systems follow emissions, with both the land and ocean sinks changing sign to become sources after the reversal from positive to negative CO\textsubscript{2} emissions (figure 1a). Lags, as quantified by the interval of maximum lagged correlation, between emissions and carbon sinks are longer (20 years) for the terrestrial carbon cycle than the ocean (11 years), with the combined land and ocean sink in between (16 years). At the point of reaching maximum cumulative emissions, the lag in land and
ocean sinks with respect to emissions means that the sinks are still positive, and thus that the atmospheric CO$_2$ concentration is already declining as emissions trend towards zero. Thus peak concentrations are reached before zero emissions, and more generally, this means that the rate of change of atmospheric CO$_2$ leads emissions, here by 13 years. This result—that atmospheric CO$_2$ change leads emissions by approximately the same timescale that sinks lag emissions—follows from the general trigonometric identity for the phase of summed functions if both emissions and sinks follow sinusoidal curves (SI text). The lead of atmospheric growth rate relative to emissions is consistent with that between diagnosed fossil fuel emissions in SSP scenarios that reach net zero as reported by ref (29) where, e.g. in the SSP5-3.4-overshoot scenario, CO$_2$ concentrations peak in 2062, while net fossil CO$_2$ emissions reach zero between 2068-2078, depending on the Earth system model.

Integrated CO$_2$ fluxes (figure 1b) show asymmetries in the accumulation of carbon during the positive and negative emissions periods. In particular, at the point of reaching zero cumulative emissions near the end of the experiment, the cumulative atmospheric sink is negative, i.e. CO$_2$ concentrations are below the preindustrial value, reaching a minimum value of 258 ppm, versus an initial value of 289 ppm and maximum value of 506 ppm (fig. 2a). Land carbon at the end is also slightly below the preindustrial value, with the excess carbon in the ocean. Looking further at the partitioning of carbon within the land and ocean systems (figs.1c-d) shows that the excess carbon is at depth, with shallow ocean DIC anomalies following closely the atmospheric timeseries and lag increasing with depth. Thus, even though the ocean shows a shorter lag than the land with respect to flux correlations against emissions, the difference at the end of the simulations is greater. The positive emissions pulse is able to propagate more fully into the deep ocean than the negative emissions pulse, leading to the positive ocean carbon difference at the end of the simulation. On land, there is likewise a difference in lags between vegetation and soil carbon (fig 1d), as well as an asymmetric response in that both lose carbon after peak emissions more rapidly than they gained carbon prior to the peak, which follows from the asymmetry of atmospheric CO$_2$ timeseries. Zonal-mean land carbon changes (fig. S3) show a stronger latitudinal dependence to the timing of soil carbon than vegetation carbon responses.

The phasing between the physical climate and CO$_2$ emissions (fig. 2a) shows that global mean surface temperature anomalies actually lead the CO$_2$ emissions, with a maximum correlation at lead of 5 years. This happens because atmospheric CO$_2$ concentrations lead emissions by more than the physical climate lags CO$_2$ concentrations. This result is consistent with, though stronger than, the current policy framework that says that reaching zero emissions will lead to effectively immediate stabilization of CO$_2$-driven global warming. Here, the suggestion from CESM2 is that CO$_2$-driven temperature stabilization may actually occur before reaching net-zero CO$_2$ emissions. Global precipitation anomalies lag both temperature and CO$_2$ emissions (fig. 2a). CESM2 has a particularly strongly negative ZEC value of -0.34C, which may be manifesting fairly soon after the emissions peak and decline, as was also found in the comparison between
ZEC diagnosed from instantaneous transition to net-zero versus gaussian emissions (17). Thus it is possible that the relative timing between achieving net-zero CO\textsubscript{2} emissions and temperature stabilization is itself dependent on ZEC.

As described above, the hypothesis here is that long-term warming after achieving net negative emissions equals the sum of cumulative emissions (CE) times TCRE, plus a committed ZEC value (13). Thus we expect that CESM2, which has a strongly negative ZEC\textsubscript{90} value of -0.34°C (17), will have an equally negative overshoot asymmetry, i.e. with colder temperatures for a given amount of cumulative emissions after reaching net-negative emission than before. This is roughly what we find (figure 2b). For most of the positive emissions period, temperature follows the expected proportionality given the previously-reported value of TCRE for the model of 2.13 degree/Eg C (16), however, the model falls off the ∆T = TCRE * CE line after emission rates begin to decline from their maximum values, and relaxes towards a line representing ∆T = TCRE * CE + ZEC, and then follows that line from the point of reaching net negative emissions through almost all the way until net cumulative CO\textsubscript{2} emissions are back to zero. After that point, global mean surface temperatures begin to rise again, even though cumulative emissions continue to fall until reaching zero.

The increase in temperatures at the end of the CESM2 simulation, when cumulative emissions are approaching zero, shows a distinct regional pattern, with maximum cooling in mid-high northern latitudes at years 200-250, followed by a reversal to warming afterwards (fig. S4a). The spatial pattern and timing relative to the reversal of CO\textsubscript{2} emissions is consistent with that observed in CESM2-WACCM for the SPP5-3.4-overshoot scenario, due to a re-strengthening of AMOC after its transient weakening with warming (13). A similar dynamic occurs here, but even more strongly, with AMOC strengthening well beyond its preindustrial value in response to the negative emissions (fig. S4b). Thus the long-timescale warming reflects the interactions between the direct forced temperature changes from CO\textsubscript{2} with the indirect response of AMOC and associated heat transport.

Any single Earth system model, such as CESM2, represents only one estimate of the complex dynamics of the Earth system. To understand more generally how the carbon-climate sensitivity metrics TCRE and ZEC govern the transient dynamics of the Earth system to an emissions reversal, we use the Finite Amplitude Impulse Response (FaIR) simple climate model (27) to perform a perturbed parameter ensemble (PPE) of simulations using the same emissions forcing pathway. We find that the 10-90th percentile range of global mean surface temperature variation in response to the forcing broadly follows the pattern of the CESM2 simulation (fig 3a). Differences between CESM2 and the FaIR ensemble are strongest at the end of the experiment, when CESM2 shows a pronounced warming due to AMOC restrengthening (a process not included in FaIR), while the FaIR simulations show a range of responses, from cooling to warming. Figure 3(b-g) shows scatterplots of TCRE and ZEC\textsubscript{100} for each ensemble against key
climate response variables. Peak warming is highly correlated with TCRE (fig. 3b-c), the lag between peak emissions and peak warming is governed primarily by ZEC (fig. 3d-e), and a weak control by ZEC on the temperature change at the end of the simulation (fig. 3f-g). We find that using both TCRE and ZEC in a multivariate linear prediction of end of simulation warming provides no additional predictive skill over using ZEC alone (not shown).

We show where in the forcing trajectory different combinations of sensitivity metrics (i.e. TCRE and ZEC at different timescales) have the strongest predictive power by plotting temperature versus cumulative emissions for each of the FaIR PPE simulations and noting where the minimum spread across the ensemble occurs (fig. 4). Normalizing the warming of each FaIR ensemble member by that ensemble’s TCRE (fig. 4a) shows a minimum ensemble spread (marked by vertical dashed lines) midway through the positive emissions phase of the simulation, with spread increasing as cumulative emissions approach their maximum. Normalizing warming by TCRE plus half of the \( \text{ZEC}_{50} \) for each ensemble member (fig. 4b) moves the minimum ensemble spread to the point of maximum cumulative emissions, i.e. half of the ZEC has already manifested in these simulations at the point of reaching zero emissions. Normalizing by TCRE plus either \( \text{ZEC}_{50} \) (fig. 4c) or \( \text{ZEC}_{100} \) (fig. 4d) shifts the point of minimum ensemble spread to either the early (fig. 4c) or middle (fig. 4d) of the negative emissions period, showing that the timescale by which ZEC is defined governs where in the negative emissions trajectory that sensitivity is realized.

The experiment here is only one realization from a wide set of possible idealized CO\(_2\) emissions reversibility experiments. Key variables that may affect the carbon and climate response are the total peak emissions and the timescale for emissions growth and reversal. We use FaIR to explore how the dynamics described above may vary in response to these alternate emissions trajectories (fig. 5). We find: (1) that the transient drop in CO\(_2\) concentrations below preindustrial values near the end of the simulation is a robust feature of any symmetric CO\(_2\) emissions reversal (fig. 5b, 5e); (2) that the peak warming amount is roughly insensitive to the timescale of emissions (fig. 5c); (3) that there tends to be a minimum in warming late in the period of net-negative CO\(_2\) emissions, which is followed by a re-emergence of warming after the negative-emissions phase (fig. 5c, 5f); (4) that the lag between peak emissions and peak warming increases with higher peak cumulative emissions (30) (fig 5f); and (5) that the long-term warming after emissions reversal is higher with higher peak cumulative emissions (fig. 5f).

**Discussion**

The Paris agreement calls for stabilization of the global climate at levels well below two degrees Celsius, and IPCC AR6 assesses that such climate stabilization requires reaching net zero CO\(_2\) emissions (IPCC, 2021). Overshoot scenarios are premised on the idea that we may be unable to avoid surpassing target warming levels, and instead may require large amounts of net-negative
CO\textsubscript{2} emissions to cool and then stabilize the climate system at the agreed warming levels. Significant climate impacts are already evident at the current warming level of 1.1 degrees Celsius. Thus future generations, if they are able to develop the means to generate the large net negative CO\textsubscript{2} emissions required for overshoot, may wish to try to restore the climate system to a preindustrial-like state, rather than stabilize it at some target level of warming well above the preindustrial. While it is not clear whether long-term CDR technologies could ever be deployed at the scale necessary to reach net negative CO\textsubscript{2} emissions (31), particularly at the scale considered here (32, 33), or, even if they could, whether the deleterious effects of these technologies would outweigh their potential benefits (33, 34), it is nonetheless important to understand how the coupled carbon and climate systems would respond to a transient reversal from net positive, through net zero, and to net negative CO\textsubscript{2} emissions in order to translate timelines of mitigation ambitions into expected climate damages.

We find that under this restoration scenario the land and ocean carbon sinks follow the trajectories of CO\textsubscript{2} emissions, becoming sources soon after emissions become negative, consistent with the results from overshoot scenarios (13, 35). The relative timing of this transition differs between land and ocean: the ocean responds in CESM2 more rapidly than land in its sink-to-source transition, even though the ocean also shows a greater stock of carbon at the end of the simulation, and thus a longer memory to carbon perturbations, than the land. This reflects that both land and ocean exchange carbon with the atmosphere at multiple timescales (36), for land due to the sequence of live and dead pools that carbon passes through, and for the ocean due to the strong gradient in timescales of carbon response to atmospheric perturbations with depth.

In this scenario, for both CESM2 and FaIR, the relationship between global mean temperature and emissions can roughly be broken into three phases. In the first phase, temperature change is proportional to cumulative emissions, with a proportionality well described by the TCRE \((\Delta T = \text{TCRE} \times \text{CE})\). This phase lasts until roughly the point where emissions rates peak. In the second phase, the influence of the ZEC begins to be felt, as the relationship shifts towards one characterized by \(\Delta T = \text{TCRE} \times \text{CE} + \text{ZEC}\). This phase begins roughly at the time of peak emissions rates, i.e. well before reaching net zero, and lasts through most of the period of net-negative CO\textsubscript{2} emissions and almost towards the point where cumulative emissions reach zero. Because much of the ZEC influence occurs before the time of reaching net zero, its magnitude governs both the timing between peak cumulative emissions and peak temperature as well as the peak warming that is reached. The third phase is characterized by long-term climate and carbon responses that govern the committed temperature change even after all anthropogenic carbon is removed from the system.

The relative lag between temperature change and emissions of CO\textsubscript{2}, as well as the remaining temperature change after reaching net zero CO\textsubscript{2} emissions, are of utmost importance to policy
and our ability to keep the climate system below warming targets. Both with CESM2 and FaIR, which between them span the range of model complexity, we find a strong relationship between the ZEC and the lag between peak cumulative emissions and peak temperature, such that if ZEC is negative then peak temperature may actually lead peak cumulative emissions.

ZEC has typically been described as the committed temperature change expected to occur a given period after reaching net zero CO₂ emissions (7, 17). However, because the standard quantification of ZEC is made relative to an instantaneous transition to zero emissions from the same 1% yr⁻¹ increasing concentration experiment (7, 17) that is also used to quantify TCRE, that quantification is also consistent with a second distinct definition of ZEC as the committed temperature change relative to expectations from TCRE proportionality at the point of reaching zero CO₂ emissions. This experiment, as well as the Gaussian emissions experiment described in ref. (17), show that the second interpretation is more correct, because the ZEC can become evident before reaching net zero CO₂ emissions when the transition occurs as part of a gradual emissions reduction. Put another way, ZEC can’t describe the amount of temperature change that is still to occur after reaching net zero when half, or even all in the case of CESM2, of that temperature change actually occurs before reaching net zero emissions. In less idealized scenarios, the relative timing between peak warming and peak cumulative CO₂ emissions will also be governed by the dynamics non-CO₂ greenhouse gasses, and in particular the relative rates of decline of cooling versus warming short-lived climate pollutants.

The ZEC governs several aspects of the global temperature dynamics in this scenario. First, ZEC governs the asymmetry in the temperature to cumulative emissions relationship between the positive and negative emissions phases. Second, because much of the ZEC occurs before reaching net zero, it affects the magnitude and governs the timing of peak global warming. IPCC AR6 assessed that the best estimate of ZEC is zero, with a likely range of ±0.3°C, and low confidence in the sign (24). If the Earth’s ZEC is negative, our findings suggest that CO₂-driven climate change may begin to reverse slightly before reaching net zero CO₂ emissions, sooner than the decade-lag that is currently estimated (15, 24), with important implications for policy.

Across all highly-mitigated CO₂ emissions trajectories, there is a consistency in the committed global warming, relative to the TCRE proportionality, upon reaching peak cumulative emissions, that is well quantified by the ZEC at various timescales, and that occurs whether subsequent emissions are net zero or net negative. If large-scale net negative CO₂ emissions are both possible and pursued, we should expect temperatures to follow the same TCRE slope in response to those emissions down almost to the point of zero cumulative CO₂ emissions, underscoring the potential efficacy of net negative CO₂ emissions for restoration of the climate system in the distant future. Lastly, the result that much of the ZEC may occur by the time of reaching net zero emissions underscores the importance of the ZEC metric, even on the short timescales required to reach net zero in order to reach Paris Agreement targets, and that better quantifying ZEC is
crucial to understand both peak CO$_2$-driven warming and the relative timing between peak warming and peak cumulative CO$_2$ emissions.

**Methods**

The annual emissions timeseries $E(t)$ [Pg C/yr] for year $t$ follows the form of the first derivative of a Gaussian:

$$E(t) = \frac{a \ (b - t) \ e^{-(b-t)^2 / 2c^2}}{c^2}$$

For the experiment here, we used values for $a$ (maximum cumulative emissions) of 1004 Pg C, $b$ (year of peak cumulative emissions) of year 150, and $c$ (timescale for emissions reversal) of 45. We used a value of $c$ 1004 Pg C, rather than 1000 Pg C, because the cumulative emissions evaluated at year 1 is 4 Pg C, thus the total integrated emissions over the period from year 1 to year 150 is 1000 Pg C, and from year 151 to year 300 is -1000 Pg C. After year 300, we set annual emissions to zero Pg C/yr. Emission fluxes are spread equally over land and ocean of the entire planet. We note that the magnitude of ZEC is itself a function of maximum cumulative emissions (17), so we use the same maximum cumulative emissions here (1000 Pg C) as in the standard ZECMIP experiment.

We use the CESM2 (26), version 2.1.3, in an emissions-driven mode, (compset ‘B1850_BPRP’) with the default initial conditions for the emissions-driven configuration (year 151 of reference (37)). For the transient simulation, all non-CO$_2$ aspects of the model were kept at preindustrial values, and CO$_2$ concentrations were prognostic in response to the specified emissions timeseries. Output fluxes and climate variables were smoothed using an 11-year Savitzky-Golay filter to remove interannual variability.

Simple climate model simulations were conducted with a large perturbed parameter ensemble using the FaIR 1.3 model (27, 28). We use 1000 ensemble members, with model radiative forcing parameters sampled following ref (27), with an extended sampling of model thermal and carbon timescale parameters sampled as detailed in Tables S1-S3, where parameter ranges are informed by a number of studies exploring the emulation of Earth System Models with an impulse response formulation (38–40). Ensemble configurations are filtered according to their ability to reproduce historical global temperature pathways as in ref. (41), leaving 207 filtered ensemble members. For each ensemble member, we calculate the response to the idealised CDR pathways, as well as standard emissions-driven metrics of TCRE (42) and ZEC (17). TCRE is here calculated as the warming in year 70 of a concentration driven simulation (where concentrations increase from pre-industrial levels at 1 percent per year until concentrations are doubled in approximately year 70) divided by compatible emissions ($E_{1\text{pct}}$) derived using an inverse FaIR simulation (27). Zero Emissions Commitment is calculated by running the forward
model with \((E_{1\text{pc}})\) until year 70, with zero emissions thereafter (7). \(\text{ZEC}_{50}\) and \(\text{ZEC}_{100}\) are measured as the temperature change between year 70 and years 120 and 170 respectively.
Figures

**Fig. 1** (a) CO$_2$ fluxes and (b) integrated CO$_2$ fluxes in response to the idealized emissions reversal scenario for CESM2. (c) Globally-integrated dissolved inorganic carbon (DIC) stock changes as a function of depth (Pg C/m) in the ocean, and (d) Globally-integrated changes in vegetation and soil (including litter and coarse woody debris) carbon stocks (Pg C) on land. Vertical dashed lines note times of peak cumulative emissions and return to zero cumulative emissions.
Fig. 2 (a) Timeseries of relative values of CO₂ emissions, global mean CO₂ concentrations, global mean surface temperature anomaly, and global mean precipitation anomaly under the idealized emissions reversal scenario for CESM2. (b) Global warming as a function of cumulative emissions for the scenario. The slope of the black line is the previously-reported value of transient climate response to cumulative CO₂ emissions (TCRE) for CESM2, and the blue line is offset from the black line by the previously-reported value of the zero emissions commitment (ZEC) for CESM2. Vertical dashed lines in (a) note times of peak cumulative emissions and return to zero cumulative emissions.
Fig. 3 (a) Range of temperature responses to idealized emissions reversal using an ensemble of FaIR simple climate model realizations. (b-g) Relationship between peak warming, lag of peak temperature to peak warming, and warming at the end of the experiment to the climate sensitivity metrics TCRE and 100-year ZEC ($ZEC_{100}$), using FaIR simple climate model. Vertical dashed lines in (a) note times of peak cumulative CO$_2$ emissions and return to zero cumulative emissions.
Fig. 4. Temperature vs cumulative CO$_2$ emissions relationship for the FaIR simple climate model ensemble driven by the idealized emissions reversal scenario. Red curves are for the positive emissions phase (years 0-150) and blue for the negative emissions phase (years 151-300) of the scenario. Panels differ in the normalization of warming for each ensemble member on the y axis, in order to show where along the trajectory each normalization minimizes the spread across the ensemble: (a) warming divided by TCRE * peak cumulative emissions (CE$_{peak}$, which equals 1000 Pg C for all ensembles); (b) warming divided by TCRE * CE$_{peak}$ + half of the ZEC$_{50}$; (c) warming divided by TCRE * CE$_{peak}$ + ZEC$_{50}$; (c) warming divided by TCRE * CE$_{peak}$ + ZEC$_{100}$. Positive emissions phase curves are foregrounded in panels a-b, negative emissions phase curves are foregrounded in panels c-d. Vertical dashed lines show the cumulative emissions that correspond to minimum ensemble spread in normalized temperature across the ensemble for
each panel, also colored by the emissions phase during which that minimum spread occurs (red=positive, blue=negative).

![Diagram](image_url)

**Fig. 5** Sensitivity to timescale and amplitude of forcing (a-c) sensitivity to timescale of carbon reversal in FaIR simple climate model. Reference case (all prior results) uses a 45 year pulse timescale and 1000 Pg C maximum cumulative emissions. Vertical dashed lines in (d-f) note times of peak cumulative emissions and return to zero cumulative emissions.

**Data availability**

All CESM2 data for the experiment described here will be made available at time of publication. All scripts to generate and analyze climate model output here are available at [https://github.com/ckoven/idealized_emissionsdriven_cdr_scenario](https://github.com/ckoven/idealized_emissionsdriven_cdr_scenario).

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References


37. Community Earth System Model developers, CMIP6 CESM2 esm-piControl experiment with CAM6, interactive land (CLM5), coupled ocean (POP2) with biogeochemistry (MARBL), interactive sea ice (CICE5.1), non-evolving land ice (CISM2.1), and CO2 concentration calculated (2019) (June 29, 2022).


Supplementary Information

To understand why the response of CO$_2$ concentrations in the atmosphere lead emissions in response to an emissions reversal, we can consider a general case of a sinusoidal emissions timeseries, that drives a combined land and ocean sink timeseries that is proportional to emissions but with an additional lag term. We can thus consider the airborne CO$_2$ change as the sum of two sinusoidal functions, for emissions and sinks respectively, and use the trigonometric identity for addition with arbitrary lags:

$$a \sin(x + \theta_A) + b \sin(x + \theta_B) = c \sin(x + \varphi)$$

Whose solution terms $c$ (amplitude) and $\varphi$ (lag) are:

$$c^2 = a^2 + b^2 + 2ab \cos(\theta_A - \theta_B)$$

$$\tan(\varphi) = \frac{a \sin(\theta_A) + b \sin(\theta_B)}{a \cos(\theta_A) + b \cos(\theta_B)}$$

In the case of the Earth system response to emissions, the sink magnitude $b$ is approximately half of the emissions $a$ (i.e. the airborne fraction is roughly $0.5$) and with a lag relative to emissions that is small relative to the timescale of emissions reversal. Thus if we set $a = 1$, $b = -0.5$, $\theta_A = 0$, and use the small-angle approximation for $\theta_B$, then we can calculate the amplitude $c$ and lag $\varphi$ of the resulting sum as:

$$c^2 = 1.25 - \cos(-\theta_B)$$

$$c \approx 0.5$$

And

$$\tan(\varphi) = \frac{-0.5 \sin(\theta_B)}{1 - 0.5 \cos(\theta_B)}$$

$$\tan(\varphi) \approx \frac{-0.5 \theta_B}{1 - 0.5}$$

$$\varphi \approx -\theta_B$$

Thus we should expect the change in atmospheric CO$_2$ to have roughly half the amplitude of emissions and lead the emissions by approximately the amount that the sink lags emissions, as is found in CESM2 here.
Supplementary Figures

**Fig. S1** (a) Timeseries of land (green), ocean (blue), and combined sink (orange) fluxes, and inferred CO$_2$ emissions (black), for CMIP6 CDRMIP 1%/yr CO$_2$ concentration reversal experiment, and (b) T vs CE plot for CMIP6 1%/yr CO$_2$ concentration reversal CDRMIP experiment (red is for increasing CO$_2$ concentrations phase, blue is decreasing CO$_2$ concentrations phase, black is for constant CO$_2$ concentration phase). Solid lines are ensemble mean and shading is +/- 1σ across ensemble. 7 Earth system models used under the CDRMIP 1%/yr forcing experiment (21): CESM2 (26), CanESM5 (43), CNRM-ESM2-1(44), UKESM1-0-LL (45), ACCESS-ESM1.5 (46), GFDL-ESM4(47), and NorESM2-LM(48). For all models, compatible emissions were calculated based on the sum of land carbon fluxes, ocean carbon fluxes, and atmospheric CO$_2$, assuming a constant conversion value of 1 ppm CO$_2 = 2.124$ Pg C(49) for all models. Data available at: CESM2: (50), CanESM5: (51), CNRM-ESM2-1: (52), UKESM1-0-LL: (53), ACCESS-ESM1.5: (54), GFDL-ESM4: (55), and NorESM2-LM: (56).
Fig. S2 (a) CO$_2$ emissions timeseries and (b) cumulative CO$_2$ emissions timeseries for SSP overshoot scenarios (c) CO$_2$ emissions timeseries and (d) cumulative CO$_2$ emissions timeseries for idealized scenario explored here.

Fig. S3 Zonal-mean trajectories of (a) vegetation and (b) soil carbon change for CESM2 simulation.
Fig. S4 (a) CESM2 Zonal-mean surface temperature anomalies, and (b) Atlantic meridional overturning circulation through the scenario.
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**Table S1:** Carbon sink timescale parameters (years) for lognormal distributions used in FaIR simple model ensemble.

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**Table S2:** Thermal sensitivity parameters in KW$^{-1}$m$^2$ for lognormal distributions used in FaIR simple model ensemble.

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**Table S3:** Thermal timescale parameters in years for lognormal distributions used in FaIR simple model ensemble.
Supplementary Information References


