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The Multi-Decadal Response to Net Zero CO_2 Emissions and Implications for Emissions Policy

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Key Points:

- The conditions for stabilization of global temperature at any level depend on the multi-century carbon and thermal cycle response
- This is described by the rate of adjustment to zero emissions parameter, spanning −0.24 to +0.17%/yr (−0.036 to 0.025°C/decade at 1.5°C)
- In 1.5°C scenarios, CO_2 emissions consistent with halting anthropogenic warming over multi-decadal timescales span −7.3 to +6.2 $GtCO_2$/yr

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract How confident are we that CO_2 emissions must reach net zero or below to halt CO_2-induced warming? The IPCC's sixth assessment report concluded that "limiting human-induced global warming to a specific level requires … reaching at least net zero CO_2 emissions." This is much stronger language than the special report on the global warming of 1.5°C, which concluded that reaching net zero CO_2 emissions would be sufficient. Here we show that "approximately net zero" is better supported than "at least net zero." We estimate the rate of adjustment to zero emissions (RAZE) parameter (−0.24 to +0.17%/yr), defined as the fractional change in CO_2-induced warming after CO_2 emissions cease. The RAZE determines the CO_2 emissions compatible with halting warming over multiple decades: in 1.5°C-consistent scenarios, CO_2 emissions consistent with halting anthropogenic warming are +2.2 $GtCO_2$/yr (5–95th percentile range spans −7.3 to +6.2 $GtCO_2$/yr), similar to the expected emissions from unmodelled Earth system feedbacks.

Plain Language Summary How confident are we that CO_2 emissions will need to reach net zero (where human-made CO_2 emissions into the atmosphere are approximately balanced with CO_2 removals through carbon capture and storage, nature-based solutions, etc.) or below to halt human-induced warming? Here we show that "approximately net zero" is the best-estimate requirement to stabilize warming. To do this we show that the behavior of the climate system's temperature response following net zero can be defined using a new parameter (the rate of adjustment to zero emissions, RAZE), which spans −0.24 to +0.17%/yr. The RAZE determines the ongoing rate of CO_2 emissions or removals compatible with halting warming. In scenarios which reach approximately 1.5°C warming, CO_2 emissions consistent with halting human-made warming over multi-decadal timescales span −7.3 to +6.2 $GtCO_2$/yr with a best-estimate of +2.2 $GtCO_2$/yr. Planning for net negative global CO_2 emissions remains important, given the chance of global temperatures overshooting 1.5°C, along with research to better understand the emissions consistent with warming stabilization.

1. Introduction

Over the last decade the ambition of global, regional and national climate policy has increasingly become defined by the date of net zero (IPCC, 2018; Masson-Delmotte et al., 2021; Stocker et al., 2013; UK Govt., 2019). This is a remarkable shift from only two decades ago when policy was instead focused on determining an acceptable level for CO_2 concentration stabilization (Prentice et al., 2001). It arises from the realization that peak global mean near-surface temperature under a CO_2 emissions driven scenario is determined by the cumulative CO_2 emissions released until the time of peak warming (Allen et al., 2009; Matthews et al., 2009), and that CO_2-induced warming only stops when CO_2 emissions reach net zero.

The Paris Agreement sets the principal aim of global climate policy to limit global warming "to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" (UNFCCC, 2015). The IPCC's special report on the global warming of 1.5°C (SR1.5) (IPCC, 2018) notes that "reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing (RF) would halt anthropogenic global warming on interdecadal timescales (*high confidence*)." These statements provide the basis for a remaining carbon budget (Matthews et al., 2020) until warming reaches a given threshold upon which CO_2 emissions must reach net zero.

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The IPCC's sixth assessment report (Masson-Delmotte et al., 2021) made a much stronger statement: "from a physical science perspective, limiting human-induced global warming to a specific level *requires* limiting cumulative CO_2 emissions, reaching *at least* net zero CO_2 emissions, along with *strong reductions* in other greenhouse gas emissions," and more specifically, "achieving global net zero CO_2 emissions, …, is a *requirement* for stabilizing CO_2-induced global surface temperature increase" (emphasis has been added where language differs from SR1.5). AR6 implies that net zero CO_2 emissions is a necessary condition to stabilize warming, while SR1.5 instead argues that net zero and declining net non-CO_2 RF is sufficient to halt warming on interdecadal timescales. This distinction is important: while both reports emphasize that halting warming requires at least an order of magnitude reduction in CO_2 emissions, SR1.5 leaves open the possibility that stabilizing warming may not require strictly net zero CO_2 emissions. AR6's statement is approximately correct (cumulative CO_2 emissions have a near-linear relationship with global warming (Allen et al., 2009)), but is not exact, and hence may be problematic if it later transpires substantial non-zero residual CO_2 emissions are consistent with stabilizing global temperatures over multi-decade intervals. Even if net zero is the best-estimate requirement for warming stabilization today, the lack of an uncertainty qualifier presents a second risk: if uncertainty in the conditions for warming stabilization is large then society must maintain the capacity to adjust carbon sinks to the emergent conditions for warming stabilization. Presenting the condition for warming stabilization as an unqualified "requirement" today implies that achieving said condition will always halt warming.

Given these concerns, we ask which of these statements is best supported by our current understanding of the physical climate system? Both refer to a physical science perspective, and are not restricted to specific scenarios. SR1.5's and AR6's scenario databases both show that the bulk of scenarios halting warming in the middle of the 21st century reach net zero CO_2 emissions, which then become net negative, along with declining net non-CO_2 RF (Huppmann et al., 2018). But most of these scenarios deliver net zero GHG emissions (evaluated with GWP_{100}) later in the century, achieving a "peak and decline" global temperature pathway. Here we focus on the physical requirements for stabilizing temperatures, a necessary condition for limiting warming to any level. Since the transient climate response to cumulative CO_2 emissions parameter (TCRE; defining the linear relationship between cumulative CO_2 emissions and resultant warming) is broadly scenario independent (Jenkins et al., 2021; Millar & Friedlingstein, 2018; Rogelj et al., 2019), the remaining carbon budget depends on: the level of anthropogenic warming at present day (Haustein et al., 2017), the TCRE parameter value, the contribution of other non-CO_2 anthropogenic pollutants (Jenkins et al., 2018, 2021; Matthews et al., 2017; Mengis & Matthews, 2020), the contribution of any Earth System feedbacks to the remaining warming, and the amount of "warming in the pipeline" (Matthews et al., 2021; Rogelj et al., 2019) following net zero CO_2 emissions. Of these, the size of this "warming in the pipeline," typically referred to as the zero emissions commitment, or ZEC (Jones et al., 2019), is crucial to answering our question on the requirements of post-net-zero CO_2 emissions policy.

The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) (Jones et al., 2019) was organized to study precisely this question: it involved a series of experiments using Earth system models (ESMs) of varying complexity (MacDougall et al., 2020) to determine the temperature behavior in the first century following the cessation of CO_2 emissions. ZECMIP's A-type experiments followed a pathway where CO_2 concentrations increased at 1%/yr until a pre-defined quantity of CO_2 has been released, and thereafter emissions become net zero and the model re-equilibrates. These experiments hint that differences in the carbon and thermal cycle responses following net zero result in a wide range of post-net zero emissions compatible with stabilized temperatures, but to date no study has focused on diagnosing them. Drawing on these experiments, below we use an idealized framework describing the multi-decade response to net zero to discuss the requirements for warming stabilization in real-world policy.

2. Characteristics of the Response to Net Zero

Using an impulse response framework we can write the surface temperature anomaly, $T(t)$, approximately as:

$$T(t) = \sum_{i=1}^{3} \frac{c_i}{d_i} \int_{t'=0}^{t} F(t')\, e^{-\frac{t-t'}{d_i}}\, \mathrm{d}t' \tag{1}$$

where $F(t)$ is the RF timeseries, and c_i and d_i are efficacies and thermal response timescales for the boxes representing heat uptake by the upper and lower ocean (Geoffroy et al., 2012). The efficacies represent the equilibrium contribution to the total surface temperature response from each box (Leach et al., 2021). Leach et al. (2021) finds that for many CMIP5/6 models two of these thermal response timescales are typically less than a decade, while the other is of order several hundred years (Leach et al., 2021; Tsutsui, 2020). Although this is not the case for every ESM, with some finding a best-fit response containing an explicit multi-decade timescale (Sanderson, 2020), most emulation parameters can be approximated using two sub-decadal and one multi-century timescale.

Using this framework, Seshadri (2017) then derives an expression (Jenkins et al., 2021; Seshadri, 2017) for the warming response to a RF timeseries $F(t)$ over a multi-decadal time interval Δt:

$$\Delta T = \kappa_F \left(\Delta F + \rho \overline{F} \Delta t \right) \tag{2}$$

where ΔT is the temperature change and $\Delta \mathrm{F}\left(\mathrm{t} - \frac{c_1 d_1}{c_2}\right) \approx \Delta \mathrm{F}$ is the change in forcing over the period Δt (for a thermal cycle with sub-decadal, d_1 and c_1, or multi-century, d_2 and c_2, timescales and associated efficiacies). $\overline{F}$ is the average forcing over the period Δt compared to preindustrial, ρ is the fractional rate of adjustment to constant forcing (RACF, in units per year) (Cain et al., 2019), and κ_F is decadal timescale thermal response efficacy or transient climate response to forcing (TCRF, in units of °C/Wm^{-2}). The RACF is small and positive ($\rho = \frac{c_2}{c_1 d_2}$), such that a constant positive RF results in slow residual warming due to the multi-century climate adjustment.

In the derivation of Equation 2, the impulse response representation of the thermal response to RF is expanded to determine the temperature anomaly over multi-decadal intervals, assuming that the system can be adequately described with timescales which are either sub-decadal or multi-centennial (Smith et al., 2018) (see discussion in Supporting Information S1). We can similarly write an impulse response representation (Joos et al., 1996) of the carbon cycle:

$$F(t) = \sum_{j=1}^{4} \mu_j \int_{t'=0}^{t} E(t') \; e^{-\frac{t-t'}{\tau_j}} \mathrm{d}t' \tag{3}$$

to determine a relationship between the CO_2 RF and cumulative CO_2 emissions. In Equation 3 τ_j are the carbon cycle response timescales and μ_j are forcing efficacies in units W/m^2/GtC for each of the four carbon pools (associated with the biosphere, upper ocean, lower ocean and geosphere). We have assumed that non-linearities in the carbon cycle response to CO_2 emissions exactly cancel with non-linearities introduced in the logarithmic relationship between CO_2 concentrations and forcing. This need not be the case, but in a wide range of climate model simulations and in the observed Earth system this appears to approximately hold true (Jenkins et al., 2018; Leach et al., 2021).

As we did for Equation 1, we expand Equation 3 over multi-decadal timescales, assuming that the four characteristic timescales representing the carbon cycle response can be split into sub-decadal (τ_1 and μ_1) and multi-century response timescales and efficacies (τ_2 and μ_2) We test the robustness of this assumption in Supporting Information S1. Rearranging for an expression for the cumulative CO_2 emissions released by time t, $G(t)$, we find:

$$G(t) = \int E(t)\mathrm{d}t \approx \frac{1}{\mu_2} \left(F\left(t - \frac{\mu_1 \tau_1}{\mu_2}\right) + \frac{1}{\tau_2} \int F(t)\mathrm{d}t \right) \tag{4}$$

This expression is similar to the expression derived having expanded the thermal cycle in Equation 2, with one term proportional to the change in RF over a time interval Δt, and the other proportional to the average RF over the interval Δt. Combining Equations 2 and 4 derives the well-known TCRE relationship—cumulative emissions are proportional to warming. Expanding the thermal and carbon cycles like this means we identify the requirements for the TCRE relationship to be time and scenario independent: the timescales in Equations 2 and 4 must exactly match $\left(\frac{\mu_1 \tau_1}{\mu_2} \equiv \frac{c_1 d_1}{c_2}; \frac{1}{\tau_2} \equiv \rho\right)$, they must not vary in time, or depend too heavily on the time history of the RF. If these conditions are met the temperature response is determined exactly over all timescales by the cumulative CO_2 emissions multiplied by a constant TCRE parameter.

If the various timescales are not identical then the temperature response can lead or lag the cumulative CO_2 emissions. Over short intervals differences between the sub-decadal timescales $\left(\frac{\mu_1 \tau_1}{\mu_2}, \frac{c_1 d_1}{c_2}\right)$ can cause some residual warming to occur shortly following net zero. However, over multi-decade intervals warming induced by mismatched short timescales quickly becomes irrelevant. More important for climate policy is the response following a CO_2 perturbation if the multi-century timescales of the carbon and thermal cycles are mismatched $\left(\frac{1}{\tau_2}, \rho\right)$. In this case, when Equations 2 and 4 are combined there is an additional term to the well-known TCRE relationship:

$$\Delta T = \kappa_E\left(\Delta G + o\overline{G}\Delta t\right) \tag{5}$$

where here $o = \rho - \tau_2{}^{-1}$ is the rate of adjustment to zero emissions (RAZE, in units per year), ρ the RACF, τ_2 is the multi-centennial carbon cycle response timescale, ΔG is the cumulative CO_2 emissions change over the interval Δt, κ_E is the TCRE parameter, and $\overline{G}$ is the cumulative CO_2 emissions released since preindustrial averaged over the interval Δt. A full derivation of Equations 2 and 4 can be found in the Supporting Information S1. The RAZE is the difference between the multi-century response of the thermal cycle ρ, and the multi-century response in the carbon cycle $1/\tau_2$. Hence, a non-zero positive RAZE (residual warming post-net zero) can arise as a result of slow carbon sinks post-net zero, or because of a fast thermal cycle supplying heat from the deep ocean (e.g., with the realized warming fraction (Millar et al., 2017) and d_2 small). Tarshish et al. (2022) discuss a similar framework describing the cause of post-net zero temperature trends to characterize the carbon and thermal cycle contributions to the spread in ZEC between ESMs.

The RAZE defines the fractional rate at which the temperature adjust over multi-decadal timescales in response to net zero CO_2 emissions following a period of positive CO_2 emissions. As the difference of two small quantities, $\rho \leq 0.3\%$/yr (Allen, Dube, et al., 2018; Allen, Shine, et al., 2018) and $\tau_2{}^{-1} \sim 0.3\%$/yr (Joos et al., 2013), the RAZE can be positive or negative with typical values of order $\pm 0.1\%$/yr (Allen, et al., 2022). Setting ΔG to zero in Equation 5 (i.e., considering a period of net zero additional CO_2 emissions) gives $\Delta T/\Delta t = \kappa_E o\overline{G} = \kappa_E oG\,(t = t_{\text{net zero}})$. The RAZE describes the development of ZEC_H, over a multi-decade interval H, where $ZEC_H = H o \kappa_E G\,(t = t_{\text{net zero}})$. This is similar to how the transient temperature response to a given emissions scenario can be characterized with the transient climate response (TCR) (Allen et al., 2022): ZEC_H (a scenario-dependent and time-dependent quantity) is characterized by the RAZE multiplied by the scenario-specific cumulative CO_2 emissions, the TCRE, and the time horizon. The RAZE determines the level of CO_2 emissions compatible with approximately constant temperatures after reaching net zero: $E_{\text{halt}} = \Delta G/\Delta t = -o\overline{G} \approx -oG\,(t = t_{\text{net zero}})$, assuming any additional emissions after warming is halted are small relative to cumulative emissions prior to that time, as will be the case on multi-decadal timescales. Typical values of RAZE and cumulative emissions released over history suggest that $oC\,(t = t_{\text{net zero}})$ is approximately 1/20th the size of anthropogenic CO_2 emissions released in 2020 (Friedlingstein et al., 2020).

3. Emissions Pathways Consistent With Halting Warming

This framework allows us to probe the requirements of emissions policy aiming to halt global warming. We now explore constraints on the RAZE parameter and E_{halt} using ESMs and the FaIRv2.0 simple climate model.

3.1. RAZE and E_{halt} Distributions From the Zero Emissions Commitment Model Intercomparison Project

RAZE parameters estimated directly from 9 ESMs and 9 EMICs from ZECMIP are shown in Table S1 in Supporting Information S1 (histograms for each experiment are shown in Figure S3 in Supporting Information S1). These are calculated using the linear gradient in the temperature response following net zero, ignoring the first decade to allow adjustments from the sub-decadal timescale responses in the carbon and thermal cycles. The mean RAZEs are −0.077%, −0.108% and −0.015%/yr in experiments where CO_2 concentrations are increased by 1%/yr until 2750, 3670 and 7330 $GtCO_2$ (750, 1000 and 2000 GtC) has been released. The RAZE appears weakly scenario dependent, although this is less pronounced than in the ZEC which, as expected, scales with cumulative emissions prior to the date of net zero (MacDougall et al., 2020). In ESMs, a negative average RAZE is observed for the 3670 $GtCO_2$ experiment, but positive average RAZE for 7330 $GtCO_2$, both based on small samples and due to a mixture of strong positive carbon-climate feedbacks and slower carbon sinks in ACCESS, UKESM and GFDL-ESM2M (such feedbacks are observed in other large perturbation experiments (Jenkins et al., 2021; Leach et al., 2021; Meinshausen et al., 2011; Millar & Friedlingstein, 2018; Nicholls et al., 2020)). In the EMICs the

RAZE is consistently negative, but still weakens as the perturbation size increases. Fortunately, policy consistent with achieving the temperature goals of Paris Agreement demands substantially lower than 7330 $GtCO_2$ cumulative emissions until the time of net zero (7330 $GtCO_2$ ~ 3.3°C CO_2-induced warming for a TCRE = 0.45°C/$TtCO_2$ (Masson-Delmotte et al., 2021)), increasing the likelihood of a small or negative RAZE according to the results of ZECMIP experiments.

Table S1 in Supporting Information S1 also shows estimates of the emissions consistent with no further warming over multi-decadal intervals (E_{halt}) for each experiment. For 3670 $GtCO_2$, the mean E_{halt} is +2.5 $GtCO_2$ (+1.9 $GtCO_2$ for ESMs only), around 1/15th of the anthropogenic CO_2 emissions released in 2020. E_{halt} scales with the size of the perturbation: higher emissions prior to net zero result in lower E_{halt}, including negative E_{halt} if the RAZE becomes positive. The mean ESM and EMIC responses suggest E_{halt} is positive following both 2750 and 3670 $GtCO_2$ perturbations (with the latter representing an approximately 1.5°C-consistent emissions budget). In all experiments E_{halt} is an order of magnitude smaller than present-day emissions, and will likely become smaller still once models routinely include additional underrepresented Earth system feedbacks.

Over multi-decadal timescales, additional non-linear effects may result from predominantly positive feedbacks which are missing from current iterations of ESMs and EMICs. These include the potential release of non-CO_2 GHGs (e.g., CH_4, N_2O) from the ocean and land biosphere, wildfire dynamics, ice-sheet-albedo feedbacks and others. IPCC's SR1.5 suggested that 100 $GtCO_2$ be removed from their remaining carbon budget estimates for 1.5 and 2°C to account for unmodelled Earth system feedbacks over the remainder of the 21st century, largely due to permafrost thawing (Forster et al., 2018; MacDougall, 2021), corresponding to additional emissions of up to +2 $GtCO_2$ per year after 2050. AR6 gave a best estimate of 26 ± 97 $GtCO_2$ per °C of warming, half the SR1.5 estimate, albeit with a large uncertainty. In the context of the ZECMIP experiments, including these unmodelled feedbacks (MacDougall, 2021) would increase the ensemble-average RAZE distribution from negative toward zero, but not enough to make it positive, at least for 1.5°C-consistent scenarios. There remains substantial uncertainty in these underrepresented feedbacks at various cumulative emissions levels (Canadell et al., 2021). Additional non-linearities may also arise over centennial-or-longer timescales where the assumptions used in deriving the RAZE response break down (Frölicher & Paynter, 2015; MacDougall et al., 2020).

3.2. Emulating the ESM Response to Net Zero

Using the FaIRv2.0 simple climate model we can emulate individual model responses to the ZECMIP experiments to confirm these direct RAZE estimates and extend the analysis to a probabilistic treatment and assessment of the impact of non-CO_2 forcing. Figure 1 shows five ESM responses to the 3670 $GtCO_2$ experiment, for which Leach et al. (2020) derive thermal cycle tunings in FaIRv2.0 (Leach et al., 2021) (ACCESS, CanESM5, CNRM, MIROC-ES2L, MPI-ESM; colored according to their TCRE value. 2750 and 7330 GtC experiments are shown in Figure S4 of Supporting Information S1). Panel a plots the CO_2 emissions, panel b the CO_2 concentrations, and panel c the global surface temperature anomaly. On the same panels smooth lines show the FaIRv2.0-derived emulated response to the same experiment, using Leach et al. (2020)'s derived thermal parameter set for each ESM and retuning the carbon cycle using the approach outlined in Jenkins et al., 2018 (see Text S1 in Supporting Information S1). For each model the temperature anomaly after net zero is successfully captured in FaIRv2.0.

Alongside the individual ESM emulations, we use FaIRv2.0 to produce an ensemble of responses to the black CO_2 emissions timeseries in Figure 1a. The responses are derived with a 10,000-member ensemble of thermal and carbon cycle parameter sets, constrained on the range of CMIP6 model responses and temperature observations (Leach et al., 2021). The sampled parameter distributions will impact on the derived distributions of RAZE and hence ZEC, particularly if there is correlation between the multi-century carbon and thermal cycle response timescales, which is not accounted for in FaIRv2.0. This produces a 10,000-member set of CO_2 concentrations and temperature response timeseries; the 5–95th, 17–83rd, 33–66th percentiles, and median responses are plotted in gray on Figures 1b and 1c. The RAZE distribution spans −0.31%/yr to +0.28%/yr, with a mean value of −0.10%/yr (shown in Figure S6 in Supporting Information S1), overlapping with the RAZE estimated with individual ESMs and EMICs in Table S1 in Supporting Information S1. Parameter sets corresponding to a smaller Realised Warming Fraction (RWF) typically result in a more positive RAZE (Frölicher & Paynter, 2015), and vice versa, supporting the derivation in Supporting Information S1.

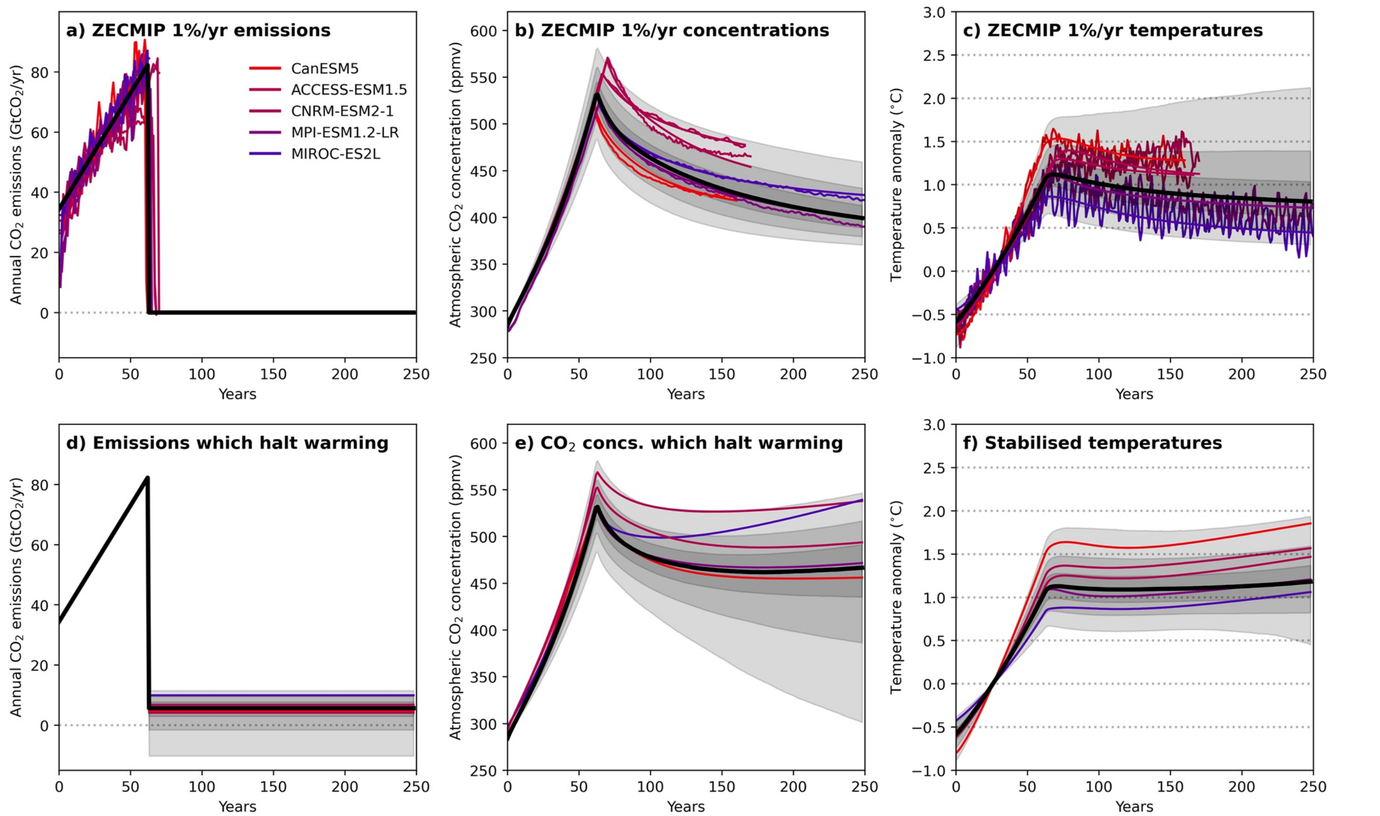

Figure 1. Response to net zero following an idealized 1%/yr concentration increase experiment. CO_2 emissions (panel a), atmospheric CO_2 concentrations (panel b) and temperature anomalies (panel c) from five ESMs contributing A-type experiments to the Zero Emissions Commitment Model Intercomparison Project study. Line colors correspond to individual model's transient climate response to cumulative CO_2 emissions values (see colorbar range below Figure S9 in Supporting Information S1, and individual model values to right of Figure 2b). FaIRv2.0 emulations are shown on top of individual model outputs. An ensemble of FaIR model runs using the black emissions timeseries (plotted in panel a) is shown in panels b and c, with shaded regions showing the 5th–95th, 17th–83rd, 33rd–66th percentiles of the distribution (solid black line shows the 50th percentile response). In panel d the CO_2 emissions are identical to the black emissions in panel a before net zero, but after they include the emissions which are consistent with no further warming (E_{halt}), for both the FaIR ensemble response (in gray) and individual ESM emulations. The CO_2 concentrations and temperature anomaly for the CO_2 emissions in panel d are plotted in panels e and f.

In FaIRv2.0 the mean E_{halt} is +3.7 $GtCO_2$/yr, with the distribution's 5–95th percentile spanning −10.3 and + 11.4 $GtCO_2$/yr (Figure 1d and Figure S9 in Supporting Information S1). The distribution is skewed toward positive residual emissions but with a tail reaching well into negative residual emissions, resulting from log-normal distributions sampled when estimating the multi-century response timescales in FaIRv2.0 (individual parameter distributions are shown in Supporting Information S1). Figure S9 in Supporting Information S1 highlights that E_{halt} is poorly constrained by the TCRE, with no correlation existing between the TCRE and RAZE parameters. As in the ZECMIP responses, net zero is not necessarily a requirement of halting CO_2-induced warming in the mean FaIRv2.0 response; around three quarters of the E_{halt} distribution lies above zero (Figure S7 in Supporting Information S1). But it is possible that net negative emissions will prove necessary—for a quarter of the ensemble negative emissions are required to halt further warming (95th percentile of −10.3 $GtCO_2$/yr, around a quarter of present-day positive emissions).

We can demonstrate that warming does indeed halt over multi-decadal intervals by rerunning the ensemble, but now including the E_{halt} in Figure 1d, with resulting plumes shown in panels e and f. Over multi-decadal intervals the E_{halt} are successfully stabilizing warming in Figure 1f. Over multi-century timescales some residual warming or cooling may occur once the RAZE approximation begins to break down. For individual scenarios the level of E_{halt} depends on the chosen thermal and carbon cycle parameters, however only in ensemble members where the RWF is very small, or where the multi-century carbon cycle response is substantially slower than the thermal cycle, do we require substantial negative emissions to halt warming. The inclusion of additional unmodelled Earth system feedbacks will push the RAZE distribution (and hence E_{halt}) closer to centering on zero.

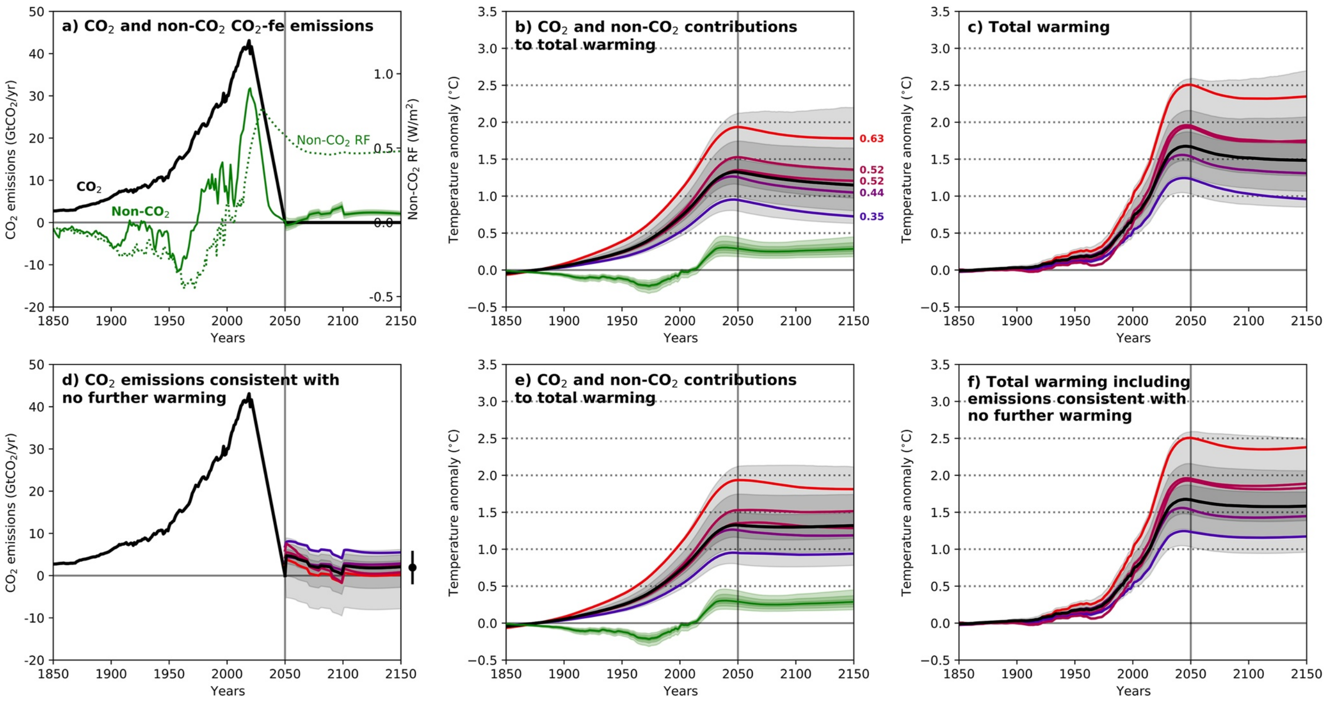

Figure 2. The response to net zero in a real-world 1.5°C-consistent scenario. Panel (a) shows the best-estimate annual CO_2 emissions timeseries from the Global Carbon Project in black, which is reduced to net zero in 2050, and the best-estimate *historical*+SSP1-19 non-CO_2 radiative forcing (RF) timeseries (green dotted line), also expressed in CO_2-forcing-equivalent terms (green solid line). For these, panel (b) shows the diagnosed CO_2 and non-CO_2 warming responses in gray and green respectively, and panel (c) shows the combined total warming plume. Panels (d, e and f) then repeat panels (a, b and c) but include the additional emissions consistent with no further warming ($E_{\mathrm{halt,total}}$). Panel d shows the black CO_2 emissions from panel a until 2050, and thereafter a plume of $E_{\mathrm{halt,total}}$. Panel e shows the corresponding CO_2 and non-CO_2 warming plumes (and the SSP1-19 non-CO_2 RF warming response in green). Panel f shows the corresponding total warming, which stabilizes over multi-decade intervals after net zero. In all panels the colored lines show five responses in FaIRv2.0 which emulate individual Earth system models (ESM), for which we have appropriate parameter sets tuned to the ESM's carbon and thermal cycle properties (see Text S1 in Supporting Information S1; color represents the relative transient climate response to cumulative CO_2 emissions value, noted to the right of panel b, with the colourbar shown below Figure S9 in Supporting Information S1 and model names from Figure 1a). A nominal missing Earth system feedback is shown for scale to the right of panel d, with magnitude +2.2 $GtCO_2$/yr (±3.7 $GtCO_2$/yr). In all panels, warming response plumes have 5th–95th, 17th–83rd and 33rd–66th percentile ranges along with the median response, and are baselined relative to 1850–1900.

3.3. The Response to Net Zero in Real World Scenarios

The RAZE distribution suggests that small residual positive emissions may be consistent with halting global warming over multi-decadal intervals in idealized CO_2-only experiments. Next, we look at how this result changes in real-world scenarios, with both a more realistic time history of CO_2 emissions and the inclusion of non-CO_2 contributions to warming.

Figure 2a shows the best-estimate CO_2 emissions timeseries from the Global Carbon Project (Friedlingstein et al., 2020) between 1850 and 2020. Beyond present day, CO_2 emissions are reduced linearly to net zero by 2050 and remain zero thereafter (black line). CO_2-induced warming is shown in Figure 2b with a gray plume, calculated using FaIRv2.0 and the same 10,000-member parameter set as in Figure 1. The CO_2-induced warming reaches approximately 1.0°C (±0.2°C) between 2010 and 2019, consistent with AR6 estimates for the CO_2 contribution to historical warming (see figure 7.8 of AR6 WG1 report (Masson-Delmotte et al., 2021)). After net zero CO_2-induced warming stabilizes (if RAZE ~0%/yr) or exhibits a small quantity of residual warming or cooling. From this ensemble we estimate the RAZE distribution (derived from the linear CO_2-induced temperature trend in years 10–100 following net zero CO_2 emissions in Figure 2b; mean = −0.09%/yr, 5–95th percentile range −0.24 to +0.17%/yr) and infer the CO_2 emissions consistent with no further CO_2-induced warming, $E_{\mathrm{halt,co_2}}$. Halting CO_2-induced warming after 2050 requires residual emissions reduced to +2.6 $GtCO_2$/yr, with a 5%–95% range of −5.1 to +7.3 $GtCO_2$/yr. Compare this to the E_{halt} estimated in Figure 1, E_{halt} = +3.7 $GtCO_2$/yr (−10.3 to +11.4) $GtCO_2$/yr, calculated from a very different CO_2 emissions scenario (a sudden cessation of emissions following a period of 1%/yr CO_2 concentration increase). The difference between these two E_{halt} estimates arises predominantly because, at the time of net zero, Figure 1's climate system is perturbed further from equilibrium than in Figure 2, where CO_2 emissions are reduced to zero over a 30-year period (which gives the climate system some time to adjust). Therefore, residual heating or cooling from historical emissions manifests to a greater extent in Figure 1, inflating the estimated E_{halt}.

Panel b also shows the warming response to the *historical+SSP1-19* non-CO_2 RF timeseries (Smith et al., 2020, 2021) (dotted line in panel a), which we include to model the warming contribution from non-CO_2 pollutants over the 21st century (green plume). SSP1-19 is chosen since it has similar policy ambition to a "net zero by 2050" CO_2 pathway. Total warming (the sum of CO_2 and non-CO_2 contributions) is shown in panel c. Alongside the plumes, five ESM emulations of this scenario (using the FaIRv2.0 parameter sets derived in Figure 1) are shown in panels b and c (color represents TCRE value, noted to right of panel b).

Stabilizing the CO_2-induced warming in panel b does not guarantee that total warming is halted—residual emissions must also account for non-CO_2 warming. To help visualize this requirement, the green plume in panel a plots the non-CO_2 RF converted into CO_2-forcing-equivalent (CO_2-fe) emissions (Jenkins et al., 2018) (the CO_2 emissions which produce the same RF as the *historical*+SSP1-19's non-CO_2 RF pathway). In SSP1-19, non-CO_2 RF increases until 2030 before declining, corresponding to CO_2-fe emissions which increase to a peak around present day, and then decline to near zero by 2030. Expressing this as CO_2-fe emissions tells us the additional CO_2 emissions we must remove from E_{halt,CO_2} to cancel out the residual non-CO_2 warming.

Heavy and sustained reliance on offsetting between long-lived with short-lived climate pollutants (SLCPs) present specific policy challenges (Allen, Dube, et al., 2018; Allen, Shine, et al., 2018; Allen et al., 2022; Cain et al., 2019). Fortunately, this is less of an issue in ambitious mitigation scenarios like SSP1-19, where the SLCP contribution to non-CO_2 RF has largely stabilized by 2050 (Meinshausen et al., 2020). Hence, CO_2-fe emissions reduce to near-zero in Figure 2a by the time of net zero, and thereafter are composed of residual long-lived pollutants and the multi-century response to stabilized SLCP emissions. It is appropriate to offset these positive CO_2-fe emissions with negative CO_2 emissions.

The sum of E_{halt,CO_2} and the inverted CO_2-fe emissions gives us the CO_2 emissions required to stabilize total warming after net zero, $E_{halt,total}$. These are plotted on Figure 2d: larger RWFs and/or $d_2 < \tau_2$ are associated with more negative RAZE and more positive $E_{halt,total}$; smaller RWFs and/or $d_2 > \tau_2$ are associated with more positive RAZE and more negative $E_{halt,total}$ (see derivation in Supporting Information S1). Around two thirds of the $E_{halt,total}$ distribution remains above zero after 2050, with best-estimate $E_{halt,total} = +2.2$ $GtCO_2$/yr (5–95th percentile range of −7.3 and +6.2 $GtCO_2$/yr). The error bar to the right of Figure 2d indicates unrepresented feedbacks causing +2.2 (±3.7) $GtCO_2$/yr emissions (equivalent to ∼180 $GtCO_2$ released 2020–2100, or +0.1°C warming), approximately the size of the permafrost thawing feedback (IPCC, 2018; MacDougall, 2021). Including unrepresented feedbacks such as this would mean that $E_{halt,total}$ will approximately centre on zero, but still with a substantial range of uncertainty.

Finally, Figures 2e and 2f show the warming response to Figure 2d's CO_2 emissions and the *historical*+SSP1-19 non-CO_2 RF. The five ESM emulations are shown in panels d, e and f, demonstrating some individual model requirements for halting warming after 2050. Since CO_2 emissions are used to offset non-CO_2 warming after net zero, CO_2-induced warming does not quite stabilize in Figure 2e. However, total warming (Figure 2f) does halt in the decades following net zero: see, for example, the edges of the warming plume after 2050 in panel c in comparison to the warming plume after 2050 in panel f (similar behavior can be seen in the individual ESM emulations using FaIR, where the warming trends in the 10–100 years after 2050 are now approximately zero in panel f).

4. Conclusions

Since the initial experiments identifying the linear TCRE relationship between cumulative CO_2 emissions and the global surface temperature anomaly in the early 2000s, the policymaking process has quickly adopted net zero as a focal point of mitigation policy. This rapid translation of an academic concept into policy reflects the considerable simplification the net zero framing offers. This work is not refuting the value of net zero as a headline target for global CO_2 emissions (the best-estimate condition for warming stabilization is very close to net zero in Figures 1 and 2). However, the precise conditions for warming stabilization are uncertain at present, and still include the possibility of requiring gigatonne-scale positive or negative CO_2 emissions over multi-decadal intervals.

Hence, contrary to the perception in policy, current evidence does not indicate that net zero CO_2 emissions are necessarily a requirement to produce no further warming over multi-decadal timescales, and both positive or negative emissions can be consistent with halting warming. This supports SR1.5's statement that "reaching and sustaining net zero CO_2 emissions and declining net non-CO_2 RF" is sufficient to halt warming, and not the stronger "requirement" of "reaching at least net zero CO_2 emissions" in AR6. In IPCC lexicon, the uncertainty qualifier which should be placed on the AR6 statement is "as likely as not," with 50% of the E_{halt} distribution lying above net zero in Figures 1 and 2. Of course, the exact requirements for warming stabilization will not be known for many decades after CO_2 emissions have been reduced by at least an order of magnitude below their current levels—the principle requirement of policy today must remain on achieving that order-of-magnitude reduction. RAZE provides additional context for policymakers on the requirements for mid-century policy: if the value of RAZE remains uncertain, then policy must maintain sufficient capacity to adjust carbon sinks to the emergent conditions for warming stabilization.

Work to better understand the mechanisms which cause the various multi-decadal warming trends post-net zero may help constrain the RAZE parameter. Work is ongoing to quantify contributions from the carbon and thermal cycle responses to produce the overall RAZE behavior in individual ZECMIP models (Tarshish et al., 2022). Continuing coordinated experiments, particularly with more realistic net zero scenarios computed using emissions-driven ESMs in CMIP7 will significantly improve our ability to constrain RAZE behavior in models, which are currently limited by the idealized nature of ZECMIP experiment setups. The newly developed Adaptive Emission Reduction Approach, for example, allows to conduct such simulations that stabilize temperature at any temperature target. Further studies must also consider the role of temporary, semi-permanent and permanent CO_2 removals in the context of warming stabilization pathways, to assess the need for geological net zero (where anthropogenic CO_2 emissions are balanced with permanent CO_2 disposal).

Residual emissions consistent with no further warming over multi-decadal intervals may be positive or negative, depending on the exact balance of multi-century carbon and thermal cycle responses, even having accounted for the residual warming from non-CO_2 pollutants, and the impact of unrepresented Earth system feedbacks. Regardless, a rapid mitigation effort reduces the risk of additional Earth system feedbacks altering the requirements for warming stabilization, and minimizes the need for active CO_2 removal to compensate for ongoing non-CO_2 emissions or to correct for any temperature overshoot.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

ZECMIP model outputs used in the production of figures are available from https://doi.org/10.5194/bg-17-2987-2020, and radiative forcing data is available at https://doi.org/10.5281/zenodo.5705391. All code to reproduce the figures is available from the corresponding author.

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