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## Decomposing drivers of global temperature change after net zero

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### Abstract

Net-zero CO<sub>2</sub> (NZCO<sub>2</sub>) and greenhouse gas emission (GHG) targets are central to the development of mitigation scenarios. Global surface air temperature (GSAT) change after NZCO<sub>2</sub> depends on several factors that broadly fall into two categories: scenario-specific factors that account for the diversity of possible mitigation pathways to net zero and beyond, and model-specific factors that describe the climate system response, captured in the zero emissions commitment (ZEC). Current established climate assessment approaches do not separate contributions from these two categories to post-net-zero GSAT change in GHG emission scenarios. To address this shortcoming, we propose a diagnostic protocol that decomposes the contributions from the model-specific ZEC and from key scenario-characteristics including non-CO<sub>2</sub> GHG reductions, net-negative CO<sub>2</sub> emissions, and other climate forcers. We assess the GSAT outcomes from a large collection of scenarios that achieve NZCO<sub>2</sub> using the MAGICC model. We find a peak warming increase of 0.09°C (likely 0.06 to 0.14°C) per decade delay in reaching NZCO<sub>2</sub> and a -0.1°C (likely -0.3 to 0.03°C) post-NZCO<sub>2</sub> GSAT decline by 2100. Based on our decomposition approach we find that the model-specific negative ZEC contributes about -0.05°C across the full scenario set. Isolating this allows us to test the sensitivity of our outcomes. We apply the IPCC AR6 WGI assessed value of 0°C (likely range ±0.19°C) for ZEC and find that the median likelihood of no further warming after achieving and maintaining NZCO<sub>2</sub> drops from 76% to just about 50%. Achieving and maintaining NZGHG, however, remains 'very likely (>90%)' to lead to no further warming outcomes for different ZEC configurations. This underlines the need for setting preventive mitigation targets to account for potential stronger than expected Earth system feedbacks and demonstrates the utility of a decomposition approach.

## Introduction

The Paris Agreement commits countries to “hold warming well below 2°C” and “pursue efforts” to limit it to 1.5°C (UNFCCC 2015). Limiting peak warming requires the achievement of net zero CO<sub>2</sub> emissions (NZCO<sub>2</sub>), where CO<sub>2</sub> emissions are balanced by an equivalent amount of CO<sub>2</sub> removed from the atmosphere and stored durably, alongside reductions in non-CO<sub>2</sub> greenhouse gas (GHG) emissions (Rogelj *et al* 2019, Rogelj and Lamboll 2024). The Agreement also establishes a broader mitigation objective: achieving a balance between anthropogenic sources and sinks of emissions (UNFCCC 2015). This has been interpreted to mean the achievement of net zero GHG emissions (NZGHG) aggregated using the Global Warming Potentials over a 100 year period (GWP100) (Schleussner *et al* 2022).

Net zero emission targets, whether for CO<sub>2</sub> or GHG emissions more broadly, have been rapidly adopted by national governments and non-state actors alike (Rogelj *et al* 2021, Ulpiani *et al* 2025). However, the warming outcomes associated with (global) achievement of net zero depend on two types of uncertainty: scenario uncertainty, arising from the range of possible emission pathways towards net zero, and climate uncertainty, arising from the physical response of the climate system (Ganti *et al* 2025). As net-zero targets become the dominant frame for mitigation commitments, clarity on what they deliver, and under what conditions, is essential for assessing their adequacy against the Paris Agreement temperature goal.

In principle, existing scenario assessment approaches adopted by the Intergovernmental Panel on Climate Change (IPCC) are well suited to investigate and partition the drivers of warming outcomes under net zero. The IPCC scenario assessment approach involves the collection of a large ensemble of scenarios from the published literature; alignment with historical emissions (harmonisation); inferring missing emission species (infilling); and a probabilistic assessment of warming outcomes using calibrated simple climate models (SCMs) (Kikstra *et al* 2022, Riahi *et al* 2022). Scenarios are subsequently categorised by peak and end-of-century warming outcomes and mitigation milestones are derived for each category (IPCC 2022).

In practice, there are two challenges with the climate-outcome-focussed categorisation approach adopted by the IPCC and subsequent scenario community efforts (Riahi *et al* 2022, 2026). First, this categorisation approach covers scenarios with a wide range of post-net-zero outcomes (both for CO<sub>2</sub> and all GHGs), making it challenging to tease out the implications of achieving specific net-zero targets and maintaining them. Second, this approach can mask the extent to which the climate outcome is a result of the SCMs’ structure and calibration, and the extent to which it results from mitigation outcomes in the emission pathways (Jenkins *et al* 2022).

A prominent example of where this bears relevance is the decline phase of 1.5°C overshoot pathways assessed in the IPCC’s 6th Assessment Report (AR6), which temporarily exceeded a global surface air temperature (GSAT) of 1.5°C before returning below that level. There is considerable uncertainty around the magnitude, even the sign, of the zero emissions commitment (ZEC), which quantifies the GSAT change following the achievement of NZCO<sub>2</sub> emissions (Palazzo Corner *et al* 2023). A ZEC of zero would indicate no further warming from CO<sub>2</sub>, while negative ZEC would lead to post-NZCO<sub>2</sub> warming decline and positive ZEC to additional warming, thus playing a central role in assessing scenario’s ability to deliver peak-and-decline behavior after exceeding 1.5°C (Schleussner *et al* 2024). The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) (Jones *et al* 2019) assessed the post-NZCO<sub>2</sub> GSAT outcomes across 18 CMIP6 Earth System Models and found a median of -0.05°C for ZEC<sub>50</sub> (ZEC realised 50 years after NZCO<sub>2</sub>) with a range of -0.36°C to 0.29°C (MacDougall *et al* 2020). Building on ZECMIP results, the AR6 Working Group I (WGI) Chapter04

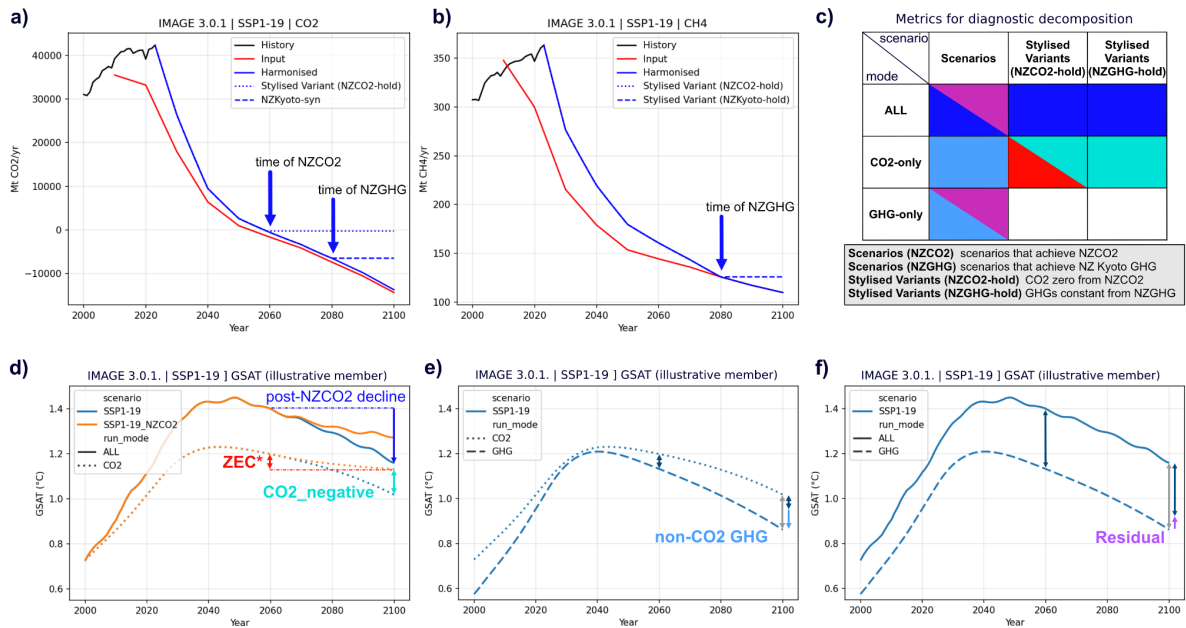
(Lee *et al* 2023) extended the analysis and found a mean value of  $-0.08^{\circ}\text{C}$  with a 5-95% range of  $-0.34^{\circ}\text{C}$  to  $0.28^{\circ}\text{C}$ . The calibrated SCMs used for the climate categorisation reflected this behaviour, and thus had a median negative ZEC (Kikstra *et al* 2022), which meant that all pathways that achieve NZCO<sub>2</sub> emissions would see warming decline, and in some cases return back below  $1.5^{\circ}\text{C}$ , even without achieving net-negative CO<sub>2</sub> emissions. AR6 WGI Chapter05 reiterated the central value for ZEC<sub>50</sub> to be  $0^{\circ}\text{C}$  with a likely (>66%) range of  $\pm 0.19^{\circ}\text{C}$ , accounting for different lines of evidence (Canadell *et al* 2021). This wide uncertainty range warrants a reexamination of how the Earth system response beyond net zero is sampled in SCMs. Specifically, we ask to what extent post-NZCO<sub>2</sub> GSAT decline can be attributed to the SCM climate response uncertainty versus scenario characteristics, such as non-CO<sub>2</sub> GHG cuts, towards and beyond net zero. Understanding this is particularly critical for the risk-based framing of climate outcomes from different mitigation pathways.

Here, we assess the likelihood and magnitude of post-NZCO<sub>2</sub> warming decline for a large number of scenarios that achieve NZCO<sub>2</sub> and a subset that achieve NZGHG using the SCM MAGICCv7.0.6a3 (Meinshausen *et al* 2011, 2020). We propose a diagnostic decomposition protocol to tease out the contributions of different drivers to post-NZCO<sub>2</sub> climate outcomes, in particular separating model-specific and scenario-specific uncertainty. We apply the decomposition to all assessed scenarios and quantify the contributions of CO<sub>2</sub> mitigation, non-CO<sub>2</sub> GHG mitigation, and net-negative CO<sub>2</sub> emissions to post-NZCO<sub>2</sub> GSAT outcomes. Finally, we re-assess the likelihood of post-NZCO<sub>2</sub> warming decline under substitution of the ZEC central estimate and likely range with the AR6 WGI assessed values.

## Methods

We use the Scenario Compass Initiative (SCI) 2025 v0.1 global pathways ensemble (Riahi *et al* 2026, Huppmann 2026) that contains a total of 1,595 unique scenarios. These are harmonised to the 2023 historical emission values in the ScenarioMIP CMIP7 historical dataset (Nicholls *et al* 2025) using the methodology developed for ScenarioMIP CMIP7 (Van Vuuren *et al* 2026) under the 7th IPCC Assessment Report cycle (AR7) (Kikstra *et al* 2026). Emission species that are necessary for the climate assessment, but either not represented or reported by individual scenarios, are infilled using the *silicone* package (Lamboll *et al* 2020) following the AR7-approach (Nicholls *et al* 2026), with those that are not yet implemented for AR7 infilled, where necessary, following the AR6-approach (Kikstra *et al* 2022). We filter for complete scenarios with no unexpected negative values that reach NZCO<sub>2</sub> before 2100 and extract the years in which they reach NZCO<sub>2</sub> and NZGHG (if applicable). The achievement of NZGHG is assessed by converting the GHGs under the Kyoto Protocol to CO<sub>2</sub> equivalents using AR6-GWP100. This leaves us with a subset of 685 scenarios that achieve NZCO<sub>2</sub> by 2100 - referred to as “Scenarios (NZCO<sub>2</sub>)” -, and a subset of 328 scenarios that achieve NZGHG by 2100 - referred to as “Scenarios (NZGHG)”.

We obtain the GSAT outcomes for all scenarios using the SCM MAGICC v7.6.0a3 (Meinshausen *et al* 2011, 2020) in its probabilistic configuration developed for the AR6 climate assessment that spans a 600 member ensemble. GSAT is derived relative to the 1850-1900 baseline for each pathway in three different modes: (1) all forcings jointly (“ALL”); (2) CO<sub>2</sub> only (“CO<sub>2</sub>”); (3) GHGs only (“GHG”) (see Figure 1c). This allows us to directly separate out the post-NZCO<sub>2</sub> contributions to GSAT change from CO<sub>2</sub> (Figure 1d) and from non-CO<sub>2</sub> GHGs (Figure 1e). A residual term (member-level difference between the ALL and GHG-only runs) accounts for the joint contribution from other forcings (Figure 1f).



**Figure 1: Diagnostic protocol design.** a) Emissions time series showing the unharmonised input (red), historical (black), and harmonised (blue) CO<sub>2</sub> emissions from a scenario selected for illustrative purposes, with indication of the years in which NZCO<sub>2</sub> and NZGHG are achieved and the Stylised Variant (NZCO<sub>2</sub>-hold) (dotted) and Stylised Variant (NZGHG-hold) (dashed) trajectories, holding emissions at the respective net-zero levels. b) as a) for CH<sub>4</sub>, accordingly only showing the Stylised Variant (NZGHG-hold). c) Matrix of scenario/MAGICC mode combinations and where in this space the inputs needed to obtain the metrics for the analysis sit, with the same color scheme as applied in panels d-f). Split cells indicate that a particular combination is required as input for multiple metrics. The grey box contains the definitions of the four pathway groups. d-f) Illustrative single member GSAT outcome from MAGICC for the same scenario, in the different run-mode configurations (“ALL” all emissions, “CO<sub>2</sub>” CO<sub>2</sub>-only, “GHG” GHG-only), showing the scenario as well as its Stylised Variant (NZCO<sub>2</sub>-hold), with the elements of the diagnostic decomposition of post-NZCO<sub>2</sub> GSAT decline: d) post-NZCO<sub>2</sub> GSAT decline as the GSAT change between the year of NZCO<sub>2</sub> and 2100 in ALL configuration; ZEC\* as the GSAT change between the year of NZCO<sub>2</sub> and 2100 in CO<sub>2</sub> configuration; CO<sub>2</sub>\_negative as the GSAT difference in 2100 between the scenario and its stylised variant; e) the non-CO<sub>2</sub> GHG contribution to GSAT change as delta in GSAT difference between GHG and CO<sub>2</sub> configuration in the year of NZCO<sub>2</sub> and 2100; f) the residual contribution to GSAT change as delta in GSAT difference between ALL and GHG configuration outcomes in the year of NZCO<sub>2</sub> and 2100.

We create two sets of stylised variants of the scenarios: for the “Stylised Variants (NZCO<sub>2</sub>-hold)”, we hold CO<sub>2</sub> at zero from the time the scenario achieves NZCO<sub>2</sub> (Figure 1a); for the “Stylised Variants (NZGHG-hold)”, we hold the Kyoto GHG emissions to the constant values that jointly achieve NZGHG from the time the respective scenario does so, maintaining the balance of forcers, which can involve negative CO<sub>2</sub> levels (Figure 1a-b). While Scenarios (NZCO<sub>2</sub>) achieve NZCO<sub>2</sub> and subsequently all contain some net-negative CO<sub>2</sub> emissions, Stylised Variants (NZCO<sub>2</sub>-hold) achieve NZCO<sub>2</sub> and then exactly maintain it. The same holds for Scenarios (NZGHG), which achieve NZGHG and subsequently all go to net-negative GHG levels to varying extents, while Stylised Variants (NZCO<sub>2</sub>-hold) achieve NZGHG and then exactly maintain it. All other forcers in the stylised variants remain identical to the scenarios. This allows us to make post-NZCO<sub>2</sub> outcomes between scenarios more comparable and to assess the effect of achieving and subsequently maintaining respective mitigation targets on GSAT across scenario groups, removing post-achievement differences in CO<sub>2</sub> or

GHGs. In particular, we use the Stylised Variants (NZCO2-hold) of the scenarios to assess the realised ZEC from the time of NZCO2 until 2100, ZEC\*, which we derive as change in GSAT from the year NZCO2 is achieved until 2100 in the Stylised Variants (NZCO2-hold) in CO2 mode, where CO<sub>2</sub> then is held at zero until 2100. As the scenarios reach NZCO2 in different years (Figure 2d), we translate ZEC\* to the established ZEC<sub>50</sub> making use of the linear relationship between ZEC\* and time between NZCO2 and 2100 (Figure 2c) through a simple scaling approach, dividing each scenario's ZEC\* value by the number of years between NZCO2 and 2100, then multiplying by 50. We assess the full distribution of ZEC<sub>50</sub> across all ensemble members and validate it against previous diagnosed values from targeted model experiments as well as IPCC AR6 WGI assessed values (S.Figure 1).

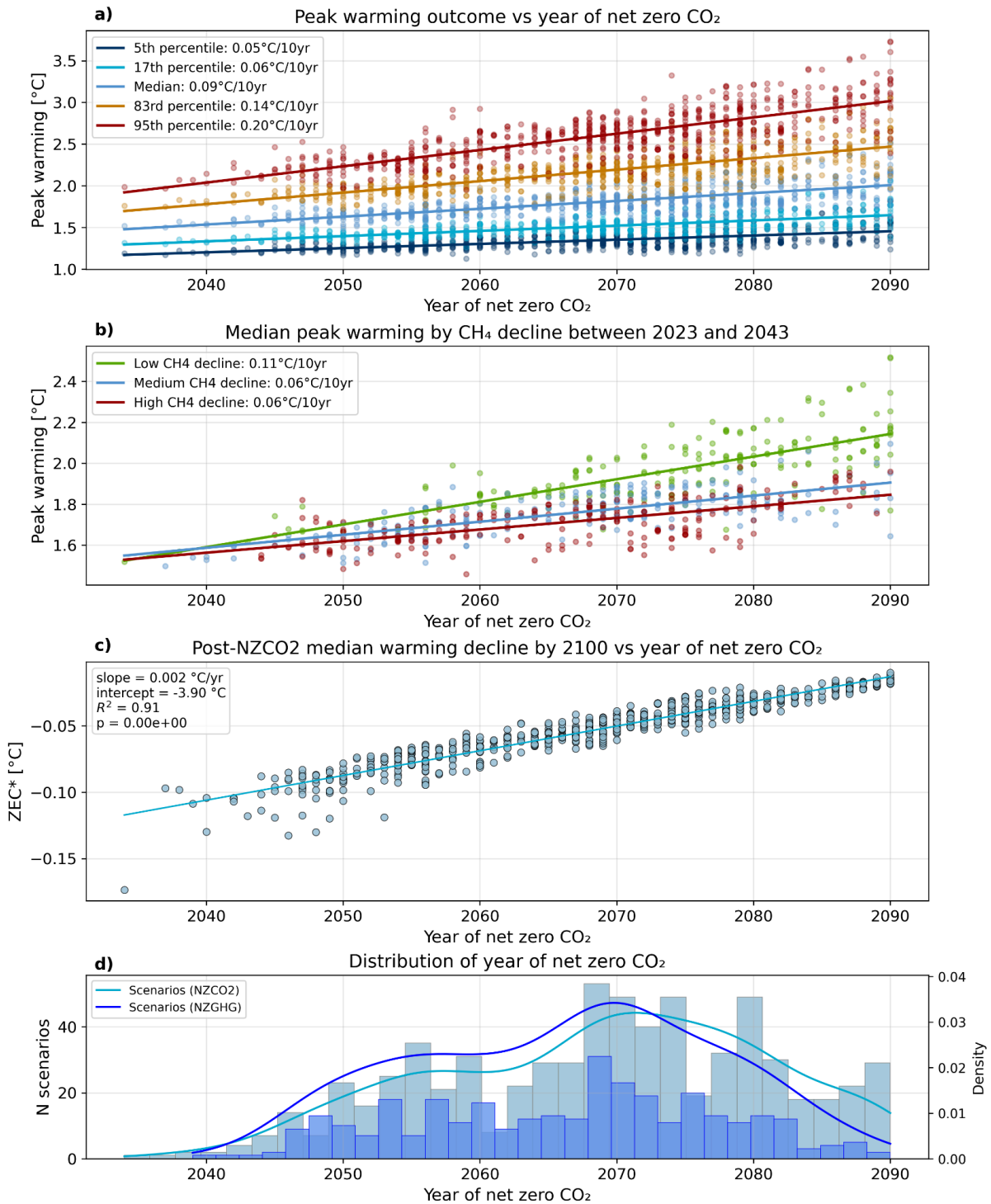
The median likelihood of post-NZCO2 GSAT decline by 2100 is computed for each scenario and its stylised variants as the fraction of ensemble members of the individual MAGICC runs that show such a decline (Table 1a). The magnitude of post-NZCO2 GSAT change is then computed for each scenario and stylised variants group as median/percentile across the scenario medians (Table 1b).

To decompose the contributions of different drivers to post-NZCO2 GSAT change, we further derive the contribution from net-negative CO<sub>2</sub> emissions as the difference between the scenarios and the respective Stylised Variants (NZCO2-hold) (Figure 1d). The contribution from non-CO<sub>2</sub> GHGs is obtained as the difference in the deltas between the ALL-mode MAGICC output and the GHG-mode MAGICC output in the year of NZCO2 and in 2100 (Figure 1e), and the residual contribution from other gases is obtained as the difference in the deltas between the GHG-mode MAGICC output and the CO2-mode MAGICC output in the year of NZCO2 and in 2100 (Figure 1f). This way, we are able to remove the GSAT changes of the pre-NZCO2 period realised by different drivers and to focus on post-NZCO2 contributions. The differences and deltas are always computed on the ensemble member-level, then statistically evaluated to obtain the scenario-wide metrics. Statements on the level of pathway groups are statistically evaluated across scenario-medians.

## Results

We analyse the dependence of warming outcomes in the assessed scenario set on the timing of NZCO2 (Figure 2). The magnitude of peak warming for the full set of Scenarios (NZCO2) increases with every decade that NZCO2 is achieved later by 0.09°C (likely 0.06-0.14°C) (Figure 2a). We also find a dependence on the strength of CH<sub>4</sub> mitigation between 2023 and 2043 with the slope of the increase of peak warming almost doubling between scenarios with Low CH<sub>4</sub> decline and scenarios with more ambitious CH<sub>4</sub> decline (Figure 2b). Further, we assess the relationship between the timing of NZCO2 and ZEC\* and apply a linear regression to the medians finding a high R<sup>2</sup>-value of 0.91 (Figure 2c). Most scenarios reach NZCO2 after 2070 (Figure 2d), with the distribution of NZCO2 year for the subset that also achieves NZGHG skewing slightly earlier. Note that the timing of peak warming does not necessarily coincide with the timing of NZCO2 (S.Figure 2).

We assess the likelihood of post-NZCO2 GSAT decline by 2100 across all four pathway groups. We find a median probability of GSAT decline by 2100 of 88% (likely 71.7 to 97.5%) across the scenarios that achieve NZCO2 and of 95.4% (likely 85.8 to 99%) across the scenarios that achieve NZGHG. This reduces to 76.2% (likely 54.2 to 85.7%) for the Stylised Variants (NZCO2-hold), and to 92.6% (likely 82.8 to 96.7%) for the Stylised Variants (NZGHG-hold) (Table 1a). This means, achieving and maintaining NZGHG increases the median likelihood of post-NZCO2 GSAT decline by 2100 by 16.4% from achieving and maintaining NZCO2 across the assessed scenarios.



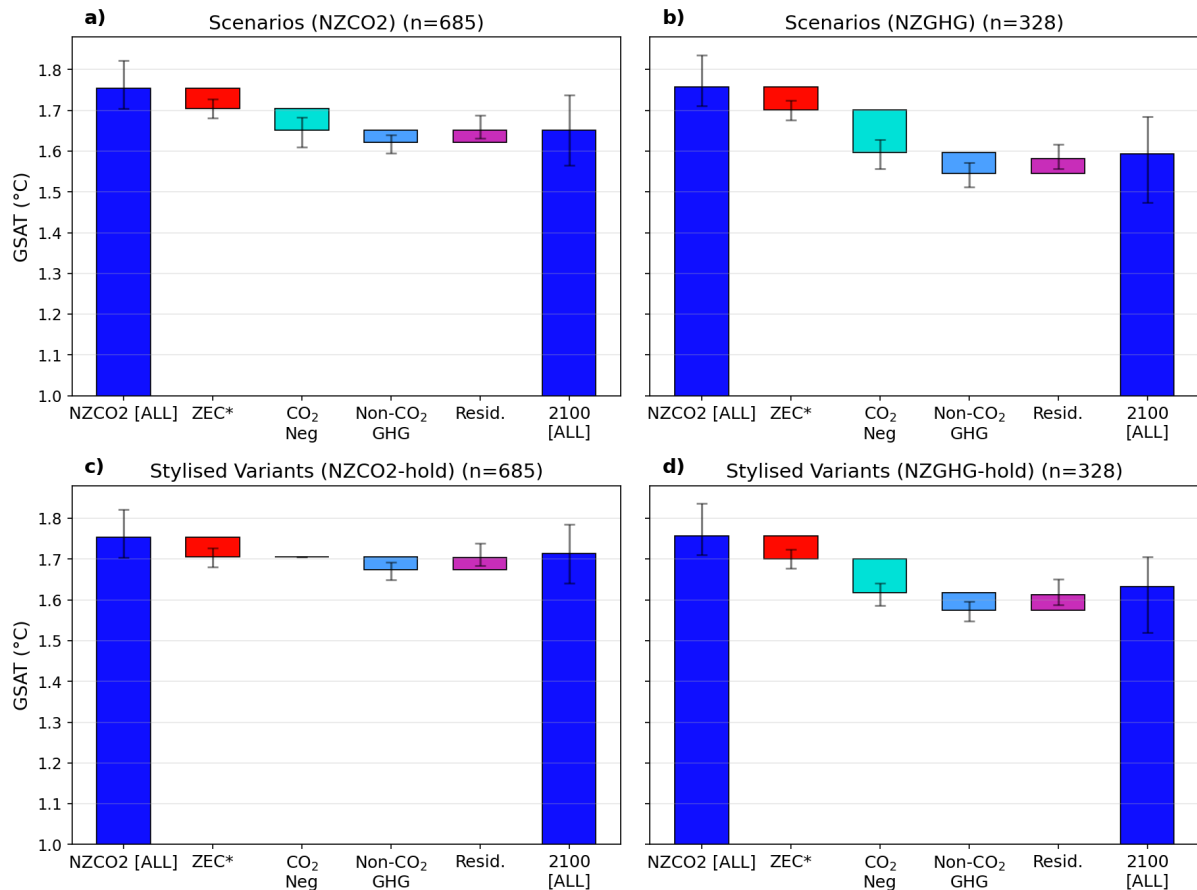
**Figure 2: Effects of the timing of NZCO<sub>2</sub> on warming outcomes of scenarios that achieve NZOC2** showing a) the change of maximum GSAT before 2100 for different percentiles with a linear regression vs. the year of NZCO<sub>2</sub>; b) the median change of peak warming outcomes vs. the year of NZCO<sub>2</sub> with the data partitioned into three evenly populated groups by the CH<sub>4</sub> decline between 2023 and 2043: Low CH<sub>4</sub> decline: -76.6 to -115.2 Mt CH<sub>4</sub>/yr; Medium CH<sub>4</sub> decline: -115.3 to -144.6 Mt CH<sub>4</sub>/yr; High CH<sub>4</sub> decline: -144.6 to -262.0 Mt CH<sub>4</sub>/yr; c) ZEC\* (the median GSAT change between the year of NZCO<sub>2</sub> and 2100) vs the year of NZCO<sub>2</sub>; d) histograms and density curves of the years of NZCO<sub>2</sub> for the set of scenarios that achieve NZCO<sub>2</sub>, as well as the subset of scenarios that also achieve NZGHG.

Assessing the magnitude of post-NZCO<sub>2</sub> GSAT change, we find a median -0.1°C GSAT change (likely -0.3 to 0.03°C) across all scenarios that achieve NZCO<sub>2</sub>, a median -0.05°C GSAT change (likely -0.18 to 0.08°C) for the Stylised Variants (NZCO<sub>2</sub>-hold), a median -0.19°C GSAT change (likely -0.36 to -0.01°C) across all scenarios that achieve NZGHG, and a median -0.15°C GSAT change (likely -0.3 to 0°C) for the Stylised Variants (NZGHG-hold) (Table 1b). Overall, the median of the scenario-level median GSAT change is negative across all scenario groups, however, likely (>66%) and very likely (>90%) ranges also include outcomes with ongoing warming.

	Scenarios (NZCO <sub>2</sub> )	Scenarios (NZGHG)	Stylised Variants (NZCO <sub>2</sub> -hold)	Stylised Variants (NZGHG-hold)
N scenarios	685	328	685	328
<b>a) Likelihood of GSAT decline by 2100 [%]</b>				
Median [%]	88.0	95.4	76.2	92.6
(p34 to p67) [%]	(81.0 to 93.8)	(92.7 to 97.3)	(68.9 to 81.2)	(89.5 to 95.3)
(p17 to p83) [%]	(71.7 to 97.5)	(85.8 to 99.0)	(54.2 to 85.7)	(82.8 to 96.7)
(p10 to p90) [%]	(63.4 to 98.8)	(80.3 to 99.7)	(47.3 to 89.4)	(77.6 to 98.2)
(p05 to p95) [%]	(52.8 to 99.7)	(75.7 to 99.8)	(39.1 to 93.0)	(72.2 to 99.3)
<b>b) Median post-NZCO<sub>2</sub> GSAT change [°C]</b>				
Median of medians [°C]	-0.10	-0.19	-0.05	-0.15
(p34 to p67) [°C]	(-0.18 to -0.03)	(-0.26 to -0.11)	(-0.10 to -0.00)	(-0.21 to -0.08)
(p17 to p83) [°C]	(-0.30 to 0.03)	(-0.36 to -0.01)	(-0.18 to 0.08)	(-0.30 to 0.00)
(p10 to p90) [°C]	(-0.37 to 0.09)	(-0.41 to 0.04)	(-0.22 to 0.16)	(-0.35 to 0.07)
(p05 to p95) [°C]	(-0.46 to 0.18)	(-0.53 to 0.11)	(-0.28 to 0.26)	(-0.42 to 0.16)

**Table 1: a) Likelihood of post-NZCO<sub>2</sub> GSAT decline between year of achieving NZCO<sub>2</sub> and 2100, computed as the fraction of scenario members with peak-and-decline behavior, and b) median magnitude of post-NZCO<sub>2</sub> GSAT change, computed on the scenario medians; showing median and percentile values for different likelihood ranges for each pathway group.**

We perform the diagnostic decomposition into ZEC\*, negative CO<sub>2</sub> emissions, non-CO<sub>2</sub> GHG mitigation, and a residual term (Figures 1, 3). For the Scenarios (NZCO<sub>2</sub>), we find contribution to post-NZCO<sub>2</sub> GSAT change of -0.05°C from ZEC\*, of -0.05°C from negative CO<sub>2</sub> emissions and of -0.03°C from non-CO<sub>2</sub> GHG mitigation, with a positive residual term of 0.03°C (Figure 3a). For the subset of scenarios that achieve NZGHG, the ZEC\* is slightly higher (-0.06°C), possibly due to scenarios in the subset reaching NZCO<sub>2</sub> slightly earlier than all scenarios taken together (Figure 2d). Negative CO<sub>2</sub> emissions contribute double (-0.1°C) to the overall higher decline of -0.19°C, and non-CO<sub>2</sub> GHG mitigation contributes -0.05°C, reflecting the higher mitigation effort required for achieving NZGHG (Figure 3b). The Stylised Variants lead to smaller overall GSAT declines compared to their Scenario counterparts, however, they agree with their Scenario counterparts on ZEC\*. The pathways that achieve and maintain NZCO<sub>2</sub> have no contribution from negative CO<sub>2</sub> emissions by design, while the contributions from the other drivers equal those of Scenarios (NZCO<sub>2</sub>) (Figure 3c). The pathways that achieve and maintain NZGHG have a contribution of -0.08°C from negative CO<sub>2</sub> emissions, of -0.04°C from non-CO<sub>2</sub> GHGs, and of 0.04°C from other gases (Figure 3d).



**Figure 3: Diagnostic decomposition of distinct contributions to post-NZCO2 GSAT change for a) the full set of Scenarios (NZCO2) that achieve NZCO2 before 2100; b) the subset of Scenarios (NZGHG) that achieve NZGHG before 2100; c) the Stylised Variants (NZCO2-hold) that achieve and maintain NZCO2; the Stylised Variants (NZGHG-hold) that achieve and maintain NZGHG; including 34th-67th percentiles as central ranges across 600 MAGICC members per scenario, with the number of scenarios per panel indicated in the panel titles.**

To validate the ZEC we first assess the relationship between ZEC\* and the year of NZCO2 and find reasonable linearity ( $R^2=0.91$ ) (Figure 2a), justifying a simple extrapolation from ZEC\* to the more established ZEC<sub>50</sub> by scaling ZEC\* from the number of years it spans (from NZCO2 to 2100) to 50 years. Across the scenario medians, we find a median ZEC<sub>50</sub> value of  $-0.08^\circ\text{C}$  with a small standard deviation of  $0.01^\circ\text{C}$ , confirming good scenario-independence of this metric. This extrapolated ZEC<sub>50</sub> is comparable to a diagnosed ZEC<sub>50</sub> ( $-0.11^\circ\text{C}$ ) of a previous model version based on abrupt emission cessation experiments (Sanderson *et al* 2024). To assess the full ZEC<sub>50</sub> range sampled by MAGICCv7.6.0a3, we compute ZEC<sub>50</sub> for all ensemble members. We find a median value of  $-0.08^\circ\text{C}$  in line with the ZECMIP central value, but the likely range is narrower and entirely negative ( $-0.01^\circ\text{C}$  to  $-0.13^\circ\text{C}$ ) (S.Figure 1). There are members with a positive ZEC<sub>50</sub>, however, the upper end of the AR6 assessed likely range is comparatively undersampled.

	Scenarios (NZCO2)	Scenarios (NZGHG)	Stylised Variants (NZCO2-hold)	Stylised Variants (NZGHG-hold)
Median [%] (ZEC50=0°C)	79.6%	97.3%	48.5%	96.0%
(p17 to p83) [%] (ZEC50=±0.19°C)	(23.4% to 99.1%)	(46.6% to 100.0%)	(1.2% to 96.1%)	(11.9% to 100.0%)

**Table 2: Likelihood of GSAT decline between year of achieving NZCO2 and 2100 with substituted ZEC<sub>50</sub> range of 0±0.19°C for the four pathway groups. We show the likelihood of post-NZCO2 GSAT decline, having substituted ZEC\* with the median and likely range for ZEC<sub>50</sub> from AR6 WGI, for each pathway group.**

To test the sensitivity of the likelihood of post-NZCO2 GSAT decline obtained in our analysis (Table 1a) to ZEC, we make use of having isolated ZEC\* in the decomposition. This allows us to replace it with the AR6 WGI assessed values (median and likely ranges) for ZEC<sub>50</sub>, scaled to the duration between NZCO2 and 2100 per scenario. This gives us projected 2100 GSAT outcomes under alternative ZEC\* values (Table 2). Under this substitution the likelihood of post-NZCO2 GSAT decline decreases for all Scenarios (NZCO2) to 79.6% (likely 23.4 to 99.1%); for the Scenarios (NZGHG) to 97.3% (likely 46.6 to 100%); for the Stylised Variants (NZCO2-hold) to 48.5% (likely 1.2 to 96.1%); and for the Stylised Variants (NZGHG-hold) to 96% (likely 11.9 to 100%). Besides decreases of the median ZEC<sub>50</sub> of up to 27.7%, the wider uncertainty range for ZEC<sub>50</sub> increases the uncertainty of post-NZCO2 decline across all scenario groups, highlighting the importance of further research aiming to reduce the uncertainty surrounding ZEC.

## Discussion

In this study, we analyse the likelihood of GSAT decline after achieving net-zero targets on 685 scenarios that achieve NZCO2 within a larger recently assembled scenario database (Riahi *et al* 2026, Huppmann 2026) using the SCM MAGICCv7.6.0a3 for the climate assessment. We apply the diagnostic decomposition protocol and separate the model-specific climate system response to NZCO2 from scenario-specific drivers of post-NZCO2 GSAT change. This decomposition allows us to isolate the model-specific ZEC, finding its central value in line with values from the literature, but with a narrower uncertainty. We, thus, recommend future SCM calibrations to aim for improved agreement with the likely range of ZEC from complex Earth System Model results, with improved sampling of the higher end of the distribution.

Our methodology has some limitations. While we are able to reduce differences between scenarios after net zero for CO<sub>2</sub> emissions and Kyoto GHGs, ongoing divergence of other species is only indirectly accounted for via the residual term in the decomposition, however, aerosol forcings may vary strongly across scenarios and can influence post-NZCO2 GSAT change in non-linear ways (Dvorak *et al* 2022). Species-level contributions derived via MAGICC-runs in different configurations are not fully additive, as they differ in terms of interaction effects across species. Further, the decomposition into model- and scenario-specific drivers only goes so far, acknowledging that the response to emissions and emissions reductions also carries some model-dependence. More complex models and targeted model experiments continue to be needed to increase process-understanding of what happens after net zero.

Due to the limited availability of scenarios that extend past 2100, our analysis is limited to end-of-century outcomes. Peak warming rarely occurs simultaneously with net zero (S.Figure 2), and a part of ZEC is realised before the time of NZCO<sub>2</sub> (Koven *et al* 2023), which our decomposition is not able to address. While we find a linear relationship between ZEC\* and the time of NZCO<sub>2</sub>, we cannot assume this relationship upholds on longer timescales (Williams *et al* 2017, Wells *et al* 2026) or under atmospheric CO<sub>2</sub> concentrations outside the range of the scenarios included here (Eby *et al* 2009, King *et al* 2024), requiring careful consideration of these factors when applying the method presented here to other scenarios.

Using the full set of scenarios in the SCI database that achieve NZCO<sub>2</sub> bypasses its extensive feasibility vetting and may, therefore, include scenarios that are not considered feasible any longer. Understanding the likelihood of post-net-zero GSAT decline under filtering by feasibility-requirements, but also along other dimensions of concern such as equity, could be addressed in follow-up work. Further, the assessed scenario ensemble is an ensemble of opportunity with no claim to complete or systematic coverage of the space of possible pathways to net zero and beyond. The presented statistical findings need to be considered with these limitations in mind.

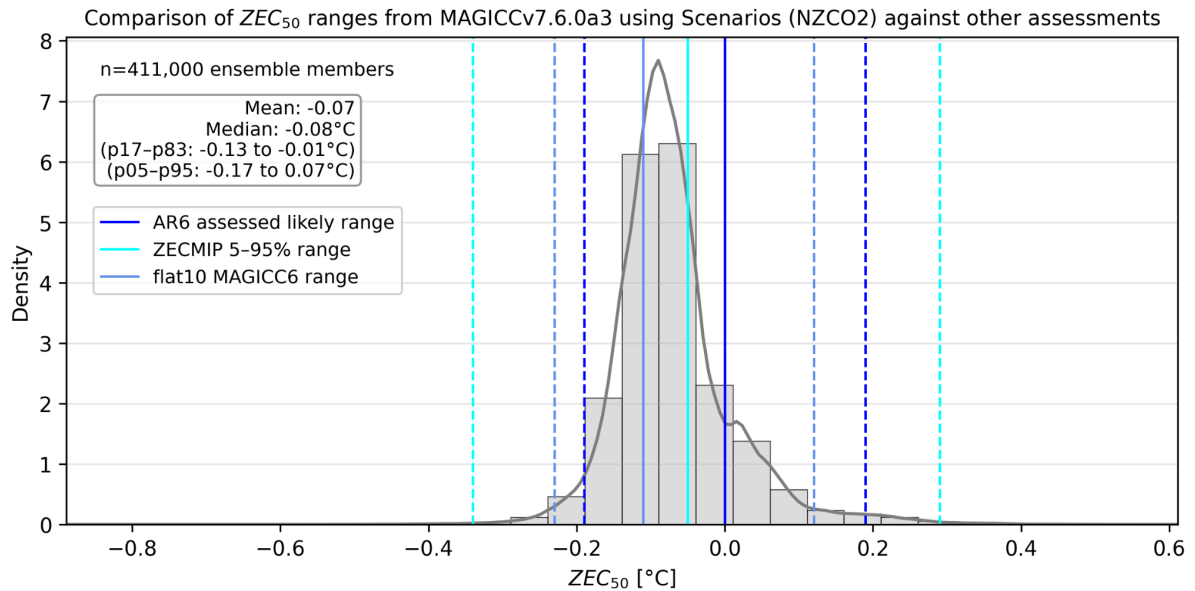
We use a hybrid infilling approach relying partly on the AR6- and partly on the AR7-approach of which a final version covering all gases is not yet available. This should be updated once the data becomes available in order to obtain conclusive values consistent with other studies of these scenarios. Applying our methodology to climate outcomes from other SCMs would also be desirable for a more complete assessment, however, exceeds the scope of this study.

ZEC is largely an effect of two competing processes: unrealised ocean warming at the time of net zero that has a post-cessation warming effect, and the ongoing removal of CO<sub>2</sub> from the atmosphere through uptake into land and ocean carbon sinks that has a cooling effect (Palazzo Corner *et al* 2023). Both these processes are represented in MAGICCv7.6.0a3. Identifying relevant parameters and mapping their effects onto the ZEC range could be useful for future calibration efforts. The uncertainty of the thermal term was recently found to be more than double as high as for the carbon term across ten Earth System Models (Sanderson *et al* 2026), suggesting particular attention should be directed here when working towards narrowing the ZEC uncertainty range.

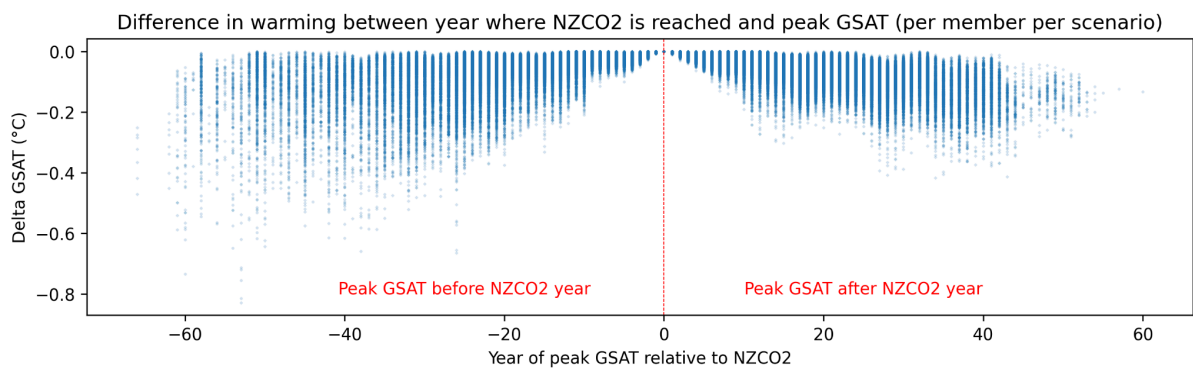
Overall, the proposed decomposition framework provides a transparent way to disentangle the influences of mitigation and the model-dependent post-NZCO<sub>2</sub> climate response and has the potential to improve the assessment of net-zero scenarios in relation to the Paris Agreement temperature goal, moving from a purely outcome-focused approach towards a driver-focused approach. We, therefore, recommend its adoption into the scenario climate assessment process. The wide uncertainty around NZCO<sub>2</sub> delivering peak-and-decline behavior in GSAT outcomes when considering the wide uncertainty of the climate system's response to net zero once more underlines the necessity of ambitious mitigation.

## Supplementary Figures

We find a member-level median value of  $-0.08^{\circ}\text{C}$  for the  $ZEC_{50}$  of MAGICCv7.6.0a3 and a likely range of  $-0.13$  to  $-0.01^{\circ}\text{C}$ , entirely below zero. We compare this against diagnosed and assessed ranges from the literature (S.Figure 1) and find overall good agreement, although the high end of the distribution is comparatively undersampled.



**S.Figure 1: Distribution of MAGICCv7.6.0a3  $ZEC_{50}$  derived from the Scenarios (NZCO2) on the ensemble member level, with the median and two likelihood ranges indicated and compared against other central values and ranges from the literature.**



**S.Figure 2: Time between NZCO2 and peak GSAT vs. the post-NZCO2 GSAT change across the Scenarios (NZCO2).**

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**Author contributions**

GG and ZN conceptualised the study. GG and AH conducted the analysis with input from ZN. AH led the writing of the manuscript with input from GG and ZN.

**Data availability**

The SCI data can be requested here: <https://scenariocompass.org/scenario-dashboard>

Access to the code can be requested here: <https://zenodo.org/records/21222216>

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