



A typology of the temperature response in overshoot, peak and decline pathways

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Abstract. As the window to limiting global warming to 1.5 °C closes, mitigation pathways consistent with this limit increasingly rely on temporary temperature overshoot. Despite recent advances in understanding how the Earth system responds to climate overshoot, uncertainty remains about the extent to which overshoot-induced changes can be reversed. Here, we synthesize the key features that determine climate reversibility and the asymmetry between responses to positive and negative emissions, challenging assumptions that net-negative emissions can undo overshoot-induced changes. We propose a typology of temperature responses in overshoot, peak and decline pathways that goes beyond established notions of reversible and irreversible climatic changes, incorporating underexplored climate feedbacks that may arise specifically during negative-emission phases. On this basis, we argue that an irreversible response, as evident from current-generation climate model simulations, cannot be ruled out. A more nuanced characterization and quantification of overshoot dynamics is critical for assessing the feasibility and risks of overshoot-based climate mitigation strategies.

1 Introduction

Limiting long-term global warming to, or as close as possible to, 1.5°C remains a central objective of international climate policy. Yet achieving this goal now almost universally requires climate overshoot associated with a temporary exceedance of temperature targets followed by substantial deployment of net-negative emissions through carbon dioxide removal (CDR) (Meinshausen et al., 2022; Bevacqua et al., 2025; Peters, 2024; Gohar et al., 2026). This has fostered research on how the Earth system responds to warming-and-reversal trajectories and the implications for climate reversibility. While many studies have explored reversibility on global and regional scales across climatic systems, including the cryosphere, biosphere, large-scale circulation, and ecosystems, Earth system components may respond in ways that are still unknown during and after climate overshoot. These scientific questions are increasingly relevant given that more than half of the scenarios suggested for the Coupled Model Intercomparison Project (CMIP) Phase 7 follow overshoot trajectories (Van Vuuren et al., 2026). Still, despite growing process understanding, remaining uncertainties around climate reversibility and symmetry in the responses to positive



and negative emissions, and current limitations in how they can be quantified, underscore the risks of overshoot and the need for early mitigation under the precautionary principle.

The latest Intergovernmental Panel for Climate Change Report (IPCC-AR6) states medium confidence in the reversibility of different climate metrics with reductions in atmospheric CO₂ and global mean temperature and that cooling from negative emissions would scale roughly linearly with cumulative CO₂ removed (Lee et al., 2021). Similarly, recent assessments on the climate response to overshoot states that deviations in the Transient Response to Cumulative Carbon Emissions (TCRE) (MacDougall, 2016; Williams et al., 2020) between positive and negative emission phases are small compared to other uncertainties for many policy-relevant pathways (Reisinger et al., 2025; Zickfeld et al., 2016, 2021; Sanderson et al., 2025b; Chimuka and Zickfeld, 2026). Here we suggest, based on recent evidence from climate model simulations, that these assessments may overlook contributions from irreversible response mechanisms under overshoot, potentially leading to an overestimation of climate reversibility and hence an underestimation of the risks associated with climate overshoot. We then conceptually synthesize key features that shape the climate response to overshoot. Expanding our knowledge on the interpretation and process-level decomposition of these response features will aid the understanding of climate reversibility in future research.

2 Criteria for Climate Reversibility

The climate reversibility concept strongly depends on whether forcing is reversible, which parts of the climate system are considered, the timescale involved, and how “return” is defined. Consequently, it has been applied inconsistently across the literature. It is therefore useful to outline the following criteria for the definition of climate reversibility:

First, a key consideration is whether the evaluation of reversibility is based on reversing the system perturbation (i.e., temperature, cumulative emission budgets or atmospheric CO₂ concentration forcings) or reversing the system state. In many studies, reversibility is defined to arise when a chosen variable, hereafter referred to as “system metric”, returns to its initial state (or toward a counterfactual reference trajectory) after the forcing is reversed (Lee et al., 2021; Winkelmann et al., 2025; Schleussner et al., 2024). If forcing reversal does not reverse the system metric, it is considered irreversible. In other studies, reversibility is defined as a gradual return to initial conditions through trend convergence rather than exact state recovery (Li et al., 2020; Rethmeier, 2025). More stringent approaches require that the post-overshoot mean state lies within the range of internal variability of an equilibrium control scenario (Schwinger et al., 2022).

Second, assessing climate reversibility depends on the system metric considered. For example, even if global mean temperature is approximately reversible after overshoot, metrics such as regional climate patterns, extreme events, or ecosystem structures are not (Schleussner et al., 2024; Pflieger et al., 2024; Kim et al., 2022; Meyer et al., 2022; Roldán-Gómez et al., 2025; Douglas et al., 2025). Similarly, carbon sinks create an asymmetry between temperature and CO₂ that prevents both from returning to pre-overshoot conditions simultaneously (Jones et al., 2016; Schwinger and Tjiputra, 2018; Keller et al., 2018a; Asaadi et al., 2024; Melnikova et al., 2021; Koven et al., 2022; Smith et al., 2026a; Park and Kug, 2022; Cao et al., 2023; Eliseev and Gizatullin, 2024). Reversibility should therefore be assessed through clearly specified metrics, including those capturing feedbacks from individual climate subsystems, rather than assumed to be a uniform property across the system. It is



also noteworthy that while irreversibility is virtually certain in many climate system metrics (Lee et al., 2021) and crucial for impacts on nature and people, it is relevant to climate reversibility only if these metrics directly affect global mean temperature.

Third, timing is a crucial determinant of reversibility. A perturbed system metric is considered irreversible on a given timescale if recovery by natural processes takes longer than the “timescale of interest” after overshoot reversal - often set to “human timescales” of around one century (Lee et al., 2021; Winkelmann et al., 2025). This means that a metric may be reversible in principle but appear effectively irreversible when assessed after a defined overshoot-and-reversal period. For example, atmospheric CO₂ concentration will decline quickly with negative emissions, while ocean carbon and heat uptake and ice-sheet dynamics will respond to forcing reductions over timescales of centuries to millennia (Schwinger and Tjiputra, 2018; Smith et al., 2026b). For these slowly responding metrics, an important distinction is whether they are reversible without further forcing reduction, or whether they require strong forcing reductions, sometimes beyond the initial conditions, to become reversible (“true” irreversibility, such as for ice sheets (Garbe et al., 2020; Gutiérrez-González et al., 2026)). This highlights the importance of distinguishing between short-term and long-term reversibility, and of evaluating not only whether reversal occurs, but also the timescale on which systems are reversible.

3 Evidence of Climate Irreversibility

Climate irreversibility reflects the Earth system’s incapacity to recover from anthropogenic forcing, showing that many climate impacts persist even after atmospheric CO₂ concentrations are reversed (Zickfeld et al., 2012; Tokarska et al., 2019). Initiatives aimed at providing a common and consistent framework to assess climate reversibility include the Carbon Dioxide Removal Model Intercomparison Project (Keller et al., 2018b) (CDRMIP; CO₂-concentration space), and the more recent flat10MIP (Sanderson et al., 2025b) (CO₂-emissions space) and Tipping Points Modelling Intercomparison Project (Winkelmann et al., 2025) (TIPMIP; temperature space). From these and adjacent efforts, climate irreversibility can be identified in many systems across the ocean (Wu et al., 2015; Palter et al., 2018; Schwinger and Tjiputra, 2018; Smith et al., 2026a; Boucher et al., 2012; Jeltsch-Thmmes et al., 2020; Tachiiri et al., 2019; Zickfeld et al., 2013; Santana-Falcón et al., 2023), the cryosphere (Smith et al., 2026b; Garbe et al., 2020; Gutiérrez-González et al., 2026; Rückamp et al., 2018; Schuster et al., 2025; Watanabe et al., 2026; Vrese and Brovkin, 2021), and land/biosphere (Melnikova et al., 2021; Koven et al., 2022; Smith et al., 2026a; Park and Kug, 2022; Asaadi et al., 2024; Munday et al., 2025). Climate irreversibility can also be exacerbated when the Earth system crosses climate tipping points - critical thresholds beyond which positive feedbacks trigger self-reinforcing transitions to alternative stable states (Winkelmann et al., 2025; McKay et al., 2022; Lenton et al., 2008; Wang et al., 2023).

The instances of irreversible behavior affecting radiative climate feedbacks or global carbon cycle dynamics exert a direct feedback on global mean temperature. This means that the effectiveness of net-negative CO₂ emissions is fundamentally limited by the path-dependence of hard-to-reverse climate response mechanisms (Schwinger et al., 2022; Jones et al., 2016; Schwinger and Tjiputra, 2018; Keller et al., 2018a; Asaadi et al., 2024; Melnikova et al., 2021; Koven et al., 2022; Smith et al., 2026a; Park and Kug, 2022; Cao et al., 2023; Eliseev and Gizatullin, 2024; Melnikova et al., 2025; Tokarska and Zickfeld, 2015; Nusbaumer and Matsumoto, 2008). This path-dependence makes emissions more effective at raising concentrations than



equivalent removals are at lowering them (Tokarska and Zickfeld, 2015; Zickfeld et al., 2016, 2021; Chimuka and Zickfeld, 2026; Chimuka et al., 2023). Ultimately, because these feedbacks can either amplify or dampen the climate response to carbon dioxide removal, returning to a specific temperature target after an overshoot may require more or less carbon removal than the original emissions-budget exceedance implies.

Recent modeling efforts show the effects of these climate responses on global mean temperature changes under climate overshoot. Figure 1 shows the climate response to flat10MIP (Sanderson et al., 2025b) idealized CO₂-emission stabilization and removal experiments (esm-flat10-zec and esm-flat10-cdr; also see (Romero-Prieto et al., 2026)) obtained from 1) the FaIR simple climate model version 2.2.3 (Leach et al., 2021) using an emission-driven 841-member parameter ensemble based on an IPCC-AR6 calibration (v1.4.0) (Smith et al., 2024) and 2) ten Earth System Models (ESMs).

FaIR's ensemble-median temperature response follows the cumulative emissions closely under positive emissions, before it starts to show stronger sensitivity to negative emissions (Fig. 1a). For the median proportionality between cumulative emissions and temperature, this means that the temperature response is asymmetric during positive versus negative emissions superimposed effect of the climate response asymmetry to negative emissions and inertia effects (Fig. 1b). Their difference at cumulative zero emissions (i.e., forcing reversal) also exceeds the deviation during the zero-emissions phase (more commonly referred to as ZEC, zero emissions commitment), indicating that FaIR's response to negative emissions is inherently asymmetric and irreversible at the time of forcing reversal. Notably, the ensemble includes members with a response less sensitive to carbon removal, which leads to irreversibility with a remaining positive anomaly. However, FaIR is structurally incapable of resolving non-linear and abrupt climate changes. It is therefore relevant to also consider the response of ESMs.

The ten ESMs also closely follow cumulative emissions (Fig. 1c). As with FaIR, the multi-model mean is more sensitive to carbon removal. However, the spread of temperature responses across models is notably large at the end of the simulation. The ESMs exhibit more variable behavior, leading to a multi-model mean response that converges to the initial state after initially diverging from a linear relationship with cumulative emissions during the emissions reversal (Fig. 1d). However, individual model responses are more diverse, with some showing significant global mean temperature irreversibility (Sanderson et al., 2025b). Although ESMs can, in principle, show non-linear climate responses owing to their high complexity, these models generally show a large degree of linearity in key climate responses, and non-linear behavior becomes apparent only in specific processes (Terpstra et al., 2025; Angevaere and Drijfhout, 2026; Drijfhout et al., 2015). Furthermore, warming of the flat10MIP scenarios effectively stays below the critical temperature of most core tipping elements (McKay et al., 2022). Thus, these ensembles leave the relative importance of non-linear and abrupt climate changes to reversibility unclear.

The zero emission commitment after 100 years of emission cessation (ZEC100) for global mean temperature is close to zero for both the FaIR ensemble median and the ESMs multi-model mean (Fig. 1e), but the range is large across both ensembles. The climate response is asymmetric between the positive and negative emission phases, with a non-negligible 10–20% (≈ 0.15 – 0.4°C) of the peak temperature (≈ 1.5 – 2.1°C) across the FaIR ensemble (Fig. 1f). Notably, more than half of the ESMs have a response asymmetry (difference between the temperature response to carbon emissions and removal) ranging 0.2– 0.5°C . This inter-model divergence is fundamentally tied to carbon sink hysteresis and ocean thermal inertia (Sanderson et al., 2025b; Zickfeld et al., 2021; Chimuka et al., 2023). Equally, the response to negative emissions is less linear than to positive emissions

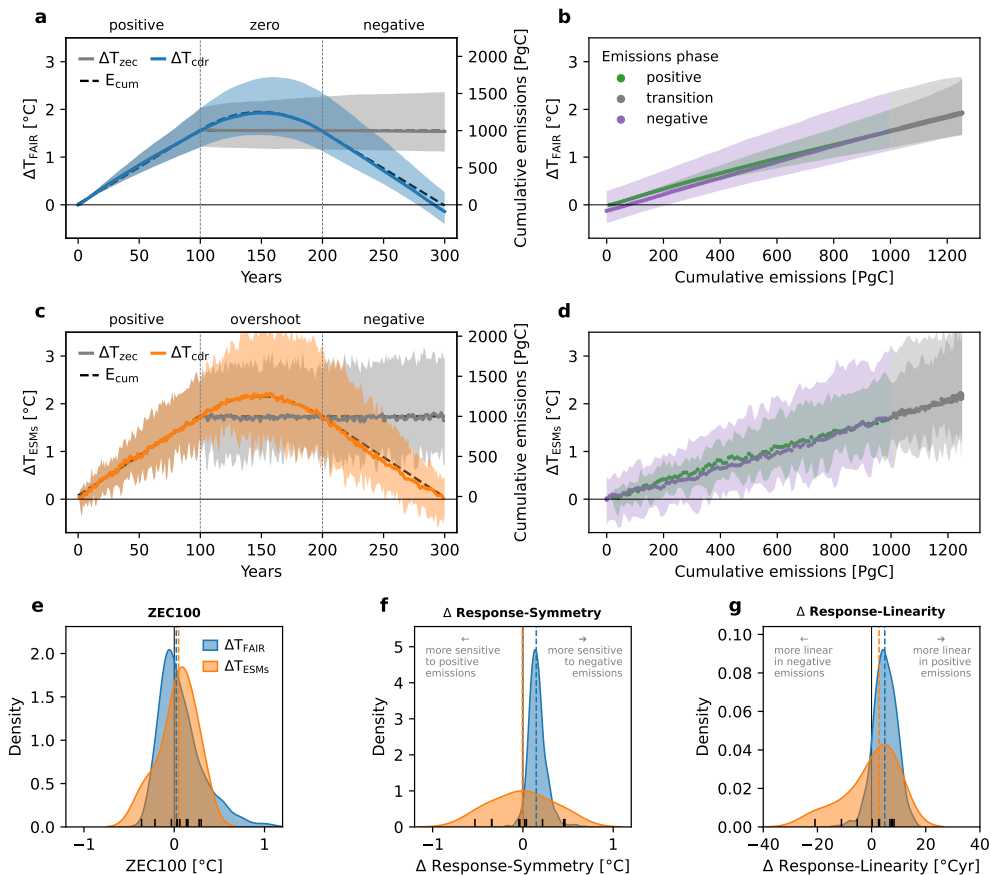


Figure 1. Climate response asymmetry and non-linearity to carbon emission and removal. **a** Surface temperature response to idealized carbon emission stabilization and removal experiments using the FaIR simple climate model with a calibrated 841-member parameter ensemble. Cumulative emissions are shown in the background (dashed black). **b** Proportionality between surface temperature and cumulative emissions during positive (green), zero (gray), and negative (purple) emissions phases. **c, d** Same as (a) and (b) for ten ESMs from flat10MIP (Sanderson et al., 2025b). Note that the removal experiment for FaIR is esm-flatX-rev, which is slightly different from esm-flatX-cdr used by the ESMs. **e** Zero Emissions Commitment after 100 years (ZEC100) of the zero emissions phase (years 100–200). Negative ZEC100 means cooling adjustment, and vice versa, during zero emissions. **f** Symmetry difference between the temperature response to carbon removal (years 200–300, i.e., after 1000 PgC of negative cumulative emissions) and emissions (years 0–100, i.e., after 1000 PgC of positive cumulative emissions). Positive asymmetry means the climate response is more sensitive to negative than positive emissions, which leads to relative cooling, and vice versa. Symmetry is only given at a value of zero. **g** Linearity difference between the temperature response to carbon removal (years 200–300) and emissions (years 0–100), measured as the cumulative deviation from a straight line between the start and end of the respective emission phases. Positive values indicate the climate response to emissions is more linear than to removals. Equal proportionality is only given at a value of zero. Note that this does not necessitate perfect linearity, but quantifies the difference in (non-)linearity.



across the majority of ensemble members for both FaIR and ESMs (Fig. 1g). ESMs again show a wide range of linearity differences, specifically with some models showing strong negative deviations from linearity. Notably, despite a similar ZEC100 range between FaIR and the ESMs, FaIR appears to tightly constrain the climate response to negative emissions, which is an optimistic result when relied on for simplified carbon budget estimates.

Currently, the reversibility effects can be within the range of other structural uncertainties (e.g., spread of climate sensitivity or carbon cycle feedback uncertainty). But when non-linear and abrupt climate changes are considered, climate irreversibility may become even more apparent. Models may disagree on the sign, and the magnitude can be small for some pathways but not universally negligible, as already seen in ESMs (Schleussner et al., 2024; Smith et al., 2026a; Sanderson et al., 2025b; Koven et al., 2023). Consequently, climate irreversibility after overshoot should not be underestimated from a precautionary perspective.

4 Key Features of the Climate Response to Overshoot

Building on evidence for climate irreversibility reported in previous studies, the climate response can be conceptually decomposed into various contributions classified as follows (Fig. 2). This classification illustrates the types of responses in example systems, but the full climate response is a superposition of multiple response features. We also note that the trajectories of the schematic scenarios illustrated herein do not illustrate non-CO₂ contributions (Matthews et al., 2020). Such contributions are generally expected to be short-lived and therefore reversible on the centennial timescales exemplified here, but because of that, could have a stronger influence on the intermediate climate evolution in lower and shorter overshoot scenarios.

A: Reversibility describes systems whose state after overshoot quickly returns to pre-overshoot conditions. Such behavior is typically found in climate system components that adjust within years, therefore following the respective forcing (Fig. 2c). The response to both the emissions (ramp-up) and removal (ramp-down) phases can be both linear and non-linear, but is always reversible at the end of the overshoot within the confines of the timescale and definition of reversibility. Hence, the response can be asymmetric yet reversible (see Box 1). These systems exhibit no long-term memory, meaning their dynamics do not significantly depend on past conditions beyond the immediate forcing. Examples include Arctic sea ice (Tietsche et al., 2011), global mean ocean mixed-layer heat content, pH, and dissolved oxygen (Li et al., 2020), and global mean precipitation (Boucher et al., 2012; Steinert et al., 2025; Walton and Huntingford, 2024). Because several climate system metrics are reversible after overshoot, these reversible systems make up a sizable part of the compound climate response after overshoot.

B1: Inertia-based hysteresis describes systems that respond slowly to changes in climate forcing, creating a response lag between ramp-up and ramp-down phases of the forcing (Fig. 2d). During the ramp-down, these systems do not immediately retrace the path followed during warming because of internal adjustment processes. Although the system temporarily deviates from the warming trajectory, it eventually returns to its original state within human-relevant timescales if emissions or temperatures remain low for long enough, without long-term persistent deviation caused by the overshoot. This behavior is not triggered by thresholds but arises purely from system inertia. Examples are ocean heat uptake and delayed release (Jeltsch-Thmmes et al., 2020), and delayed forest recovery after overshoot (Munday et al., 2025; Park and Kug, 2022). By definition,

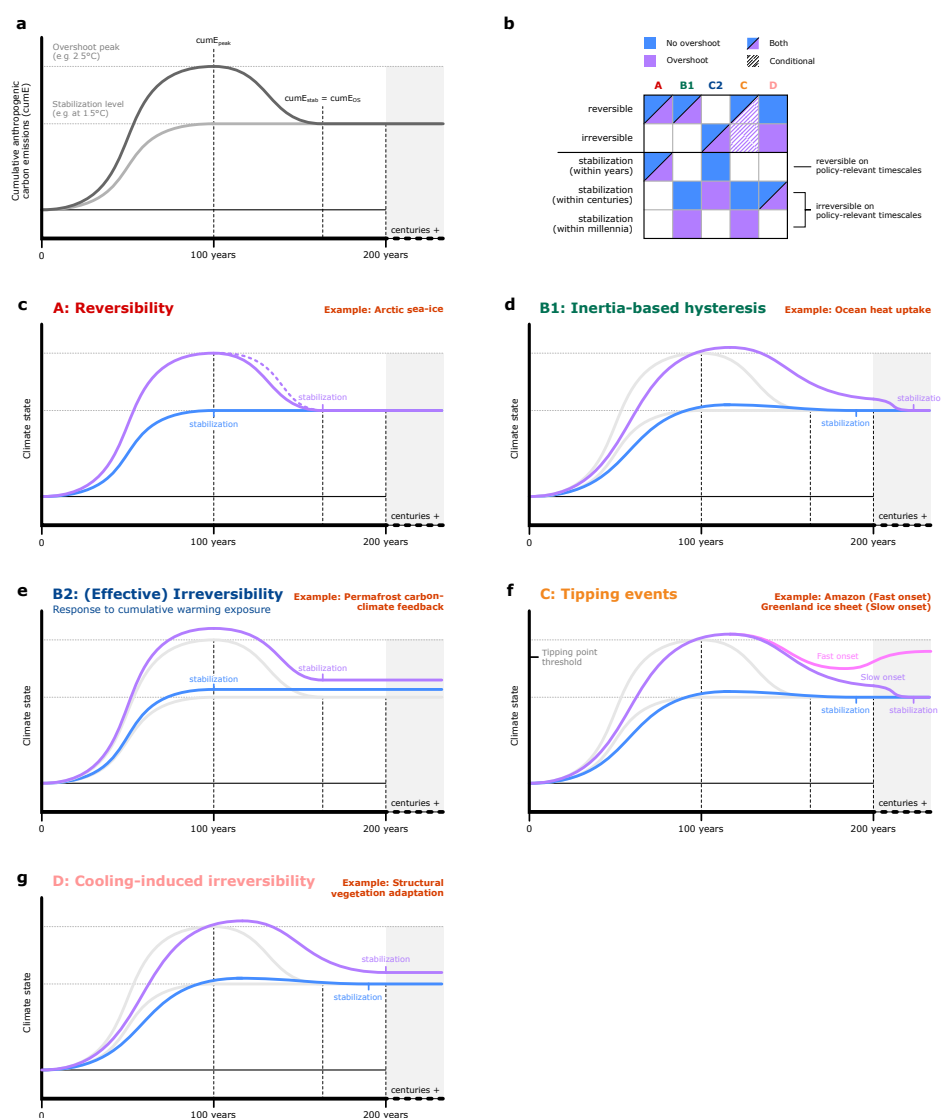


Figure 2. Schematic illustration of the key features of the climate systems response to overshoot. a Cumulative emissions scenarios of idealized overshoot and non-overshoot (stabilization) pathways, which reach the same cumulative emissions level after overshoot. The dashed line illustrated cases that are asymmetric and nonlinear, yet still reversible (also see Box 1). **b** Overview table of characteristics for each response feature for reversibility/irreversibility and response time scales. **c–g** Schematic illustration of response features A–D in response to the scenarios in panel (a), with example systems (top right). This classification illustrates example response types, but the full climate responses would comprise a compound of multiple of these features. Note that there is a non-defined likelihood for responses to fall on the other side of the reference line, i.e., a more sensitive system leads to larger reversibility, and a system state lower than the reference.



these processes are irreversible at the time of the return of an emissions overshoot, but are reversible given a significant time lag.

Box 1. Concept clarification: climate response reversibility, linearity and symmetry

Climate reversibility, linearity, and symmetry describe distinct aspects of the climate response and should not be conflated. Reversibility refers to whether the system returns to its initial (or counterfactual non-overshoot) state once forcing is restored (Fig. Box 1a). Linearity refers to a proportional relationship between forcing and response, such that changes in temperature scale directly with cumulative emissions and the response to combined forcings equals the sum of the individual responses. Symmetry concerns whether the pathways of warming and cooling follow the same (shape of) trajectory.

Often asymmetry arises from non-linear responses, but it can also arise in otherwise linear responses if the response to carbon emissions (TCRE) differs from that of carbon removal (TCRR), while inherently being irreversible (Fig. Box 1b). In contrast, state-dependence in the climate system can be fully reversible yet asymmetric: for example, the cooling trajectory may initially deviate from the warming trajectory but converge back to the same state once cumulative emissions are restored (Fig. Box 1c). If non-linearity and asymmetry combine, the climate response becomes irreversible by definition (Fig. Box 1d).

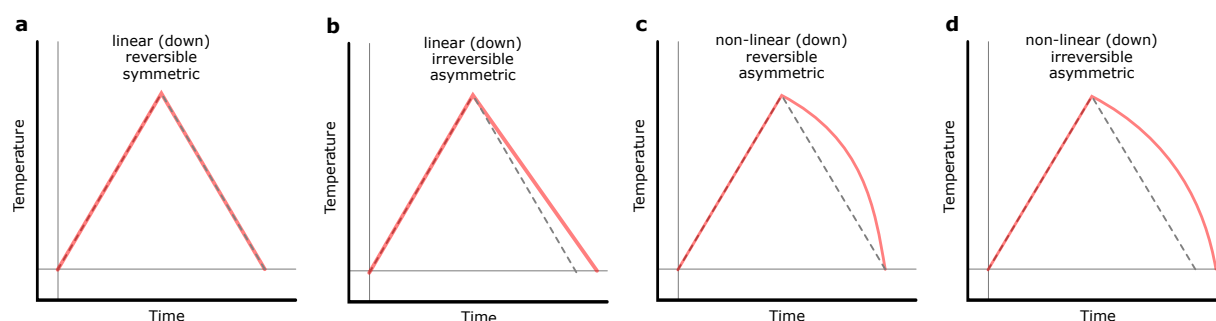


Figure Box 1. Schematic of the temperature response (red solid) to forcing (gray dashed) illustrating differences and combinations for the concepts of climate response reversibility, linearity and symmetry. Note that there could be a total of eight combinations; however, two of them are conceptually impossible, and two would assume strong non-linear temperature change to cumulative emissions - therefore not matching reality.

B2: Irreversibility describes systems where gradual but cumulative changes occur in response to sustained warming, producing long-lasting impacts that do not reverse on centennial timescales, even if the forcing returns to lower levels (Fig. 2e). As such, they describe a response similar to inertia-based hysteresis (B1), but on much longer timescales. This implies that these processes are reversible in principle, but effectively irreversible on human-relevant time horizons. These irreversible responses



165 are often linear to cumulative warming exposure (Schleussner et al., 2024; Steinert et al., 2026; Dickau et al., 2026), where subsequent cooling, at best, slows further progression. The associated (globally aggregated) response is neither catastrophic nor abrupt but arises from slow and persistent changes. Examples include permafrost carbon loss, where thawed carbon is released into the atmosphere but cannot be re-sequestered quickly (Nitzbon et al., 2024), and long-term sea-level rise from ice sheet mass loss (Golledge, 2020; Klose et al., 2024).

170 **C: Tipping events** occur when systems cross critical thresholds (i.e., tipping points) that activate internal positive feedbacks, driving a self-sustaining and often abrupt transition to a qualitatively different state (Winkelmann et al., 2025; McKay et al., 2022; Wang et al., 2023). State transitions due to tipping events are inherently nonlinear, and once initiated, they rapidly reorganize the system in ways that cannot be reversed simply by returning forcing to lower levels (Fig. 2f). A defining feature of tipping dynamics is strong hysteresis because the reverse tipping point, if it exists at all, lies far below the original threshold, 175 meaning that cooling must go well beyond pre-tipping conditions to restore the earlier state. These processes lead to alternative stable states that are maintained by internal feedback loops rather than continuous external forcing. Climate overshoot is generally expected to increase the risk of tipping (Ritchie et al., 2026; Wunderling et al., 2023; Möller et al., 2024), but its behavior can vary between slow-onset and fast-onset tipping. When exposed to the same overshoot trajectory, slow-onset systems can withstand a temporary crossing of their tipping point, which makes them generally less prone to tipping than fast- 180 onset systems, which rapidly transition when their feedbacks dominate (Ritchie et al., 2026, 2021). Examples are the dieback of the Amazon rainforest induced by hydrological feedbacks (Flores et al., 2024) and the collapse of the Atlantic Meridional Overturning Circulation triggered by freshwater input (Chapman et al., 2024; Romanou et al., 2023; Alkhayouon et al., 2019; An et al., 2021; Weijer et al., 2019; Oh et al., 2025) (both fast onset), or the irreversible shift of West Antarctic Ice Sheet grounding lines due to marine ice-sheet instability (Garbe et al., 2020; Feldmann and Levermann, 2015; Waibel et al., 2018) 185 and Greenland Ice Sheet melt via albedo–elevation feedbacks (Robinson et al., 2012; Gregory et al., 2020) (both slow onset).

D: Cooling-induced irreversibility occurs when the cooling after overshoot amplifies prior disturbances or triggers new feedbacks that would not appear under monotonic or stabilized warming. As such, these feedbacks emerge specifically during rapid cooling after overshoot (Fig. 2g). During warming, adaptation processes such as physiological, structural, ecological, or systemic adjustments closely follow the warming trajectory. However, the adjusted systems become maladaptive during 190 subsequent cooling, preconditioned by the warming phase, with reduced resilience, viability, or functionality. Hence, these systems experience irreversible change solely as a consequence of the cooling. These feedbacks are also inherently rate-dependent. Maladaptation of systems leads to cooling-induced irreversibility under rapid cooling. But slow enough cooling lets them readjust themselves. This behavior differs from tipping dynamics (C) - which occur regardless of whether temperatures continue to rise or stabilize, as warming alone does not induce abrupt regime shifts in C. Equally, it differs from classic 195 irreversibility (B2) because the system responds linearly during warming and becomes irreversible only due to cooling. Since the change is permanent rather than temporary, it also differs from inertia-based hysteresis (B1). Examples can be found in vegetation, biological, and ecosystem processes such as vegetation structural shifts, where favorable climate conditions during the warming phase may push vegetation beyond carrying capacity, leaving ecosystems more vulnerable to later climate stress



and legacy climate effects during the cooling phase of overshoot (Zhang et al., 2021, 2024; Gray and Brady, 2016; Jump et al., 2017; Varney et al., 2026). Further examples are overshoot-related alterations of species habitats (Morée et al., 2025).

5 Simplified compound response archetypes

The response to overshoot may form four qualitatively distinct archetypes of climate reversibility depending on how the described features form a superimposed response: 1) “Climate Recovery”, 2) “Climate Commitment”, 3) “Overcompensation”, and 4) “Runaway Climate”. Note that we do not assign any likelihoods to these archetypes here; our classification is purely qualitative. This classification can then be interpreted in terms of known diagnostic climate response metrics used to characterize the transient and long-term response of global temperature to carbon emissions and removals (also see Appendix A). We will here focus on the Transient Response to Cumulative Carbon Emissions (TCRE), the Zero Emission Commitment (ZEC) and the Transient Response to Cumulative Carbon Removals (TCRR).

During transient warming ramp-up, the TCRE relationship is approximately linear (Tokarska et al., 2016; Matthews et al., 2009; Allen et al., 2009). When emissions cease, the global temperature continues to evolve, with either warming, cooling, or a cancellation of both, depending on how global carbon cycle and heat uptake dynamics respond to zero emissions (MacDougall et al., 2020; Palazzo Corner et al., 2023; Sanderson et al., 2026). ZEC is expected to take centuries to be fully realized. Because negative emissions often commence before temperature is in equilibrium with past emissions, it can be split into ZEC at the time when emissions switch from zero to negative emissions, and a residual (ZEC_{resid}) that unfolds during negative emissions. ZEC is also state-dependent, meaning it can produce different temperature evolutions depending on the amount of emissions before zero emissions commence (Ehlert and Zickfeld, 2017; Palazzo-Corner et al., 2025; MacDougall et al., 2020; Gibbs et al., 2026). Part of ZEC is also assumed to be realized before the cumulative emissions peak, which drives a deviation from TCRE proportionality already during part of the warming phase (Schwinger et al., 2022; Koven et al., 2023). In the case of climate overshoot, TCRR can be asymmetric to TCRE (Zickfeld et al., 2016, 2021; Chimuka and Zickfeld, 2026). In addition, there are non-negligible contributions to the full response from non-linear feedback, which can further differentiate responses to negative versus positive emissions.

5.1 Symmetric climate response to positive and negative emissions

Figure 3 shows a schematic of the relationship between global mean temperature and cumulative emissions for various qualitative combinations of the quantities for TCRE, ZEC and TCRR in an idealized overshoot scenario (positive-, zero-, and negative emissions phases). Initially, the climate response is expected to follow a quite linear TCRE relationship during emissions ramp-up. If the climate response to overshoot were completely symmetric, the temperature curve would follow the TCRE and TCRR lines (dotted black), and ZEC (and therefore also ZEC_{resid}) would be zero. This describes the archetypes of “Climate Recovery”, where reversal of pre-overshoot conditions occurs when system metrics largely return to their pre-overshoot trajectories dominated by reversibility (response feature A), implying limited to no long-term climate hysteresis. Such cases would support



230 the viability of overshoot scenarios in climate policy because the system response is linear and the associated climate impact risks reverse.

5.2 Asymmetric climate response to positive and negative emissions

If ZEC is positive (Fig. 3a,b), temperature follows cumulative emissions as expected from the theoretical TCRE relationship but starts to deviate toward higher cumulative emissions because part of the ZEC warming commitment is already realized
235 before emissions reach zero (Koven et al., 2023). Less abrupt emission cessation leads to a larger fraction of ZEC materializing before emissions turn zero. Positive ZEC then leads to warming during the zero-emissions phase. For ZEC to substantially affect the temperature trajectory, a long zero-emission phase is required (this effect is exaggerated for illustration purposes in Figure 3). When TCRE is equal to TCRR, reversibility is solely determined by ZEC (not shown in Fig. 3; red arrow would be zero). When TCRR is smaller than TCRE (i.e., a climate response less sensitive to negative emissions than to positive
240 emissions), the temperature increasingly deviates from the theoretical TCRE relationship, which leads to large irreversibility (Fig. 3a). This is caused by a combination of the residual warming from non-equilibrated ZEC-induced inertia, asymmetry between TCRE and TCRR, and additional non-linear climate feedbacks. This is the “Climate Commitment” archetype, where partial reversibility reflects incomplete system recovery after overshoot. Some system metrics remain altered despite declining forcing, leaving persistent legacy effects from system inertia (B1) and irreversibility (B2).

245 In the opposite case of TCRR larger than TCRE (i.e., a climate response more sensitive to negative emissions than to positive emissions), warming from a positive ZEC is dampened by TCRR-induced cooling, which leads to weaker irreversibility (Fig. 3b). Note that depending on the magnitude of ZEC and shape of TCRR, the temperature during the removal phase may cross that of the emissions phase. This is the “Overcompensation” archetype, where climatic feedbacks or carbon-cycle responses may drive the system beyond its original baseline in the opposite direction, thereby potentially overcompensating
250 the climate overshoot and producing cooler or more stabilized conditions than before the overshoot.

The same cases can be constructed for negative ZEC (Fig. 3c,d), whereby a net cooling is either dampened by TCRR larger than TCRE (Fig. 3c) or exaggerated by TCRR smaller than TCRE (Fig. 3d). Both “Climate Commitment” and “Overcompensation” archetypes can occur under these conditions too, and despite their opposite directions, they would mean equal effects on irreversibility to initial climate conditions. While current-generation ESMs indicate both positive and negative ZEC responses
255 (Sanderson et al., 2025b; MacDougall et al., 2020), the consequences for global mean climate irreversibility are equivalent, regardless of their sign.

Figure 3 omits the influence of more complex response features (e.g., C and D as described in Sect. 4). During both the positive and negative emissions phases, nonlinear responses from tipping events and cooling-induced transitions may affect irreversibility, as partially seen in ESMs (Sanderson et al., 2025b; Koven et al., 2023). The risk of tipping events increases with
260 the magnitude and duration of overshoot (Ritchie et al., 2026; Wunderling et al., 2023; Möller et al., 2024), but a reduction in warming and tipping risk in the overshoot scenario may be compensated for by inertia-based hysteresis (B1) and cooling-induced irreversibility (D) or by the superposition of tipping processes and carbon cycle change under negative emissions. The impact magnitude of cooling-induced transitions is highly uncertain as they have not yet been consistently considered

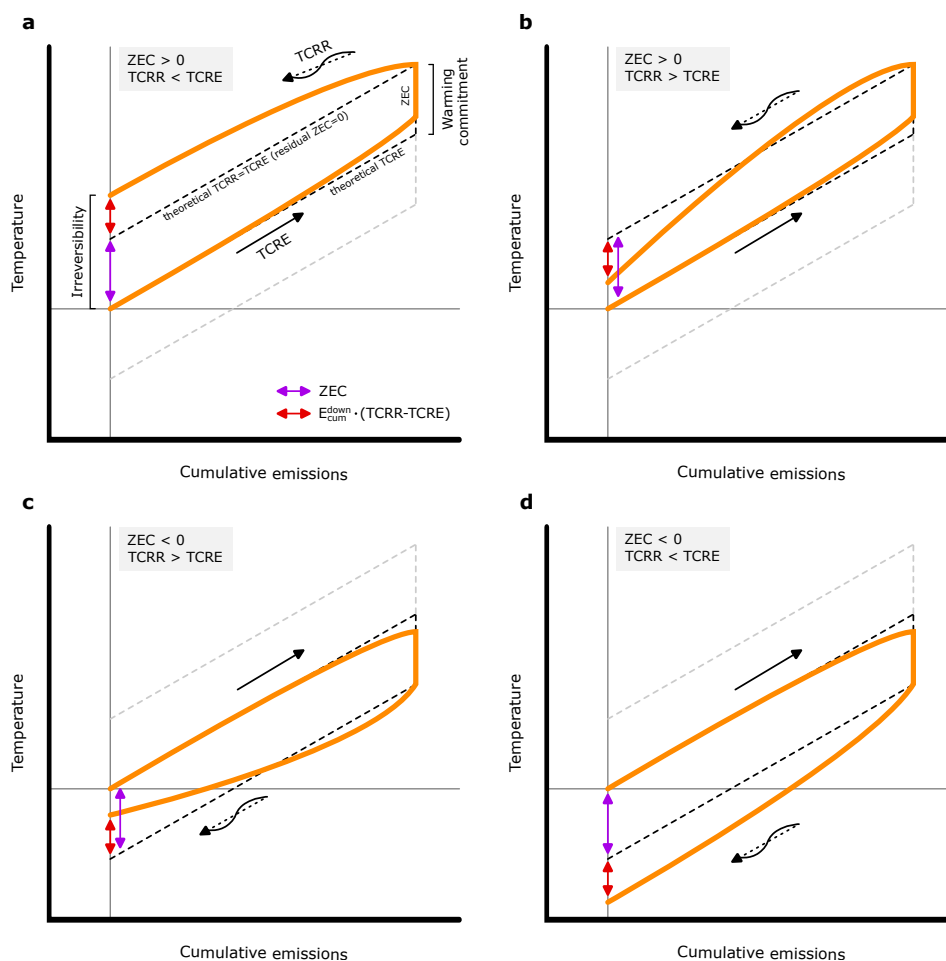


Figure 3. Schematic illustration of asymmetric temperature responses to overshoot in emissions space. **a** Schematic relationship between global mean temperature and cumulative emissions in response to an idealized overshoot scenario (positive-, zero-, negative emissions phases; following a esm-flat10-rev trajectory) for cases of positive ZEC and TCRR smaller than TCRE (indicating that the full climate response during the negative emissions phase is less sensitive than during the positive emissions phase). **b–d** Same as (a) for different combinations of ZEC and the TCRR–TCRE relationship, which strongly affects the magnitude and sign of irreversibility after the overshoot. Note that the TCRR response as illustrated here does not explicitly include the residual term type C and D response features (see Appendix A). Also, the response ZEC and irreversibility magnitudes and the response linearity are exaggerated and idealized for illustration purposes. E_{cum}^{down} denotes cumulative carbon removal.

265 contributors to climate irreversibility. An extreme outcome from these irreversibility features is the “Runaway Climate”, which arises when self-reinforcing feedbacks after tipping events dominate, causing continued warming or state change even after forcing is reduced (Steffen et al., 2018; Ripple et al., 2026).



Together, the different archetypes illustrate how overshoot pathways can lead to divergent long-term trajectories depending on feedback strength, system inertia, and tipping dynamics. For overshoot scenarios, this suggests an asymmetry in the climate response to cumulative negative carbon emissions, rather than a linear relationship between temperature and cumulative carbon removal.

6 Conclusions

The Earth system's response in climate overshoot, peak and decline scenarios may be irreversible. In combination, the climatic response features described in this Perspective challenge the assumption that emissions removal equal to historical emissions can fully reverse climate change. It underscores that temperature recovery after overshoot may be neither immediate nor reliably proportionate to cumulative negative emissions and leaves an unknown probability that overshoot-based pathways are riskier (Schleussner et al., 2024; Ripple et al., 2026; Drouet et al., 2021). Moreover, declines in global temperature do not ensure the reversibility of regional climate (Schleussner et al., 2024; Pflaederer et al., 2024; Roldán-Gómez et al., 2025; Douglas et al., 2025), ecosystem impacts, and socio-economic damages, and the most severe impacts may fall on populations that contributed least to the problem, reinforcing that early and rapid mitigation is safer, more equitable (Kruczkiewicz et al., 2025) and likely cheaper (Drouet et al., 2021; Riahi et al., 2021).

We argue here that a combination (and absence) of the response features detailed herein can be used to represent the full climate response to overshoot. To our knowledge, there is currently no climate modeling framework that can realistically account for all the climate response features discussed here. Specifically, cooling-induced reversibility (feature D) has, to our knowledge, not been addressed comprehensively. Real-world impacts of this feature may range from negligible to comparable with inertia-based effects, and therefore represent a research priority. Future methodological advancements are therefore needed to more confidently assess the climate response to overshoot. This includes representing CDR activities in novel modeling frameworks (see Appendix B) in ways that allow assessment of both their effectiveness and biogeophysical side-effects (Schwinger et al., 2026). The effects of such activity-driven CDR implementations themselves might impact regional or even global reversibility - something that the Carbon Dioxide Removal Model Intercomparison Project Phase 2 for CMIP7 aims to address.

Due to the non-negligible risk of climate irreversibility after overshoot, climate policy should move beyond end-of-century targets to consider the full temporal consequences of overshoot pathways. Regardless, reducing emissions rapidly in the near term remains the most reliable way to minimize both peak warming and the need for large-scale carbon removal, thereby avoiding unintended consequences from overshoot pathways.

Code and data availability. The flat10MIP data is available via Sanderson et al. (2025a). Code for reproducing the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.6084/m9.figshare.31926558>.



Appendix A: Framework for Mapping Response Features to Climate Metrics

The emission-driven temperature response (T_{rev}) to overshoot, peak and decline pathways can be expressed as the sum of the responses to cumulative positive (TCRE) and negative (TCRR) emissions ($E_{\text{cum}}^{\text{tot}} = E_{\text{cum}}^{\text{pos}} + E_{\text{cum}}^{\text{neg}}$), an inertia-based adjustment
300 formulated as ZEC (here $ZEC = ZEC + ZEC_{\text{resid}}$), and a compound of residual terms Δ_X , determined by state-dependent climate feedbacks, nonlinear transitions including tipping events, and processes emerging uniquely under net-negative emissions, broken down into the different climate response features A–D:

$$T_{\text{rev}} = \underbrace{E_{\text{cum}}^{\text{pos}} \cdot \text{TCRE} + E_{\text{cum}}^{\text{neg}} \cdot \text{TCRR}}_{\text{A}} + \underbrace{ZEC + ZEC_{\text{resid}}}_{\text{B1}} + \sum_{X \in \text{B2}, \text{C}, \text{D}} \Delta_X \quad (\text{A1})$$

The first two summands of Equation A1 represent feature A (Reversibility). Because the inertia-based ZEC contribution
305 (representative of feature B1: Inertia-based hysteresis) is expected to take centuries to reach equilibrium, it is split here into the ZEC where emission cessation switches from zero to negative emissions, and a residual ZEC_{resid} contribution under negative emissions. Note that 1) $ZEC = 0$ when there is no zero emission period (i.e., immediate transition from positive to negative emissions), then all ZEC contribution is attributed to ZEC_{resid} ; 2) if the zero emission phase is long enough to fully realize ZEC under zero emissions, then $ZEC_{\text{resid}} = 0$; and 3) if $ZEC_{\text{resid}} \neq 0$, then ZEC_{resid} is considered the ZEC-equivalent
310 that now unfolds under negative emissions. ZEC may already modify the temperature time series before peak emissions, and may approximate an asymmetry between TCRE and TCRR if the following terms are negligible (Koven et al., 2023). This assumption works well for some models and breaks down for others (Sanderson et al., 2025b), either because of system dynamics or because of a lack of modeling capability to represent additional response features.

Further, Δ_X in the last term takes different forms depending on the response feature. The contributions of Δ_{B2} (Irreversibil-
315 ity) can be approximated by impulse response functions with one or more exponential decay terms (representing response timescales), which create lags between the emissions forcing and the climate response. Feature C's response contribution Δ_C (Tipping events) can further be described by a multiplicative response term, classically in the form of a logistic function, which represents an (abrupt) transition between two stable system states. Such a transition can be determined by factors that initiate the state transition, such as crossing a critical temperature threshold or the rate of carbon emissions, which is highly system-
320 specific (Ashwin et al., 2012). It should be noted that both overshoot and non-overshoot warming scenarios have certain risks of triggering climate tipping points, depending on the level of maximum warming in each, which in both cases can add to the deviation from the TCRE/TCRR relationship. However, the risk is higher under overshoot and its contribution to climate irreversibility depends on the characteristics of the overshoot trajectory (Ritchie et al., 2026; Wunderling et al., 2023; Möller et al., 2024). Lastly, the response contribution Δ_D (Cooling-induced irreversibility) can be defined analogously to C, in that it can
325 be thought of as a conditional tipping-like process that only becomes relevant once emissions turn negative. Specifically, this means that the logistic state transition is here conditioned by (the rate of) negative emissions, which would not have occurred under warming alone.



Appendix B: Modeling Framework to Assess Climate Responses in Overshoot, Peak and Decline Pathways

A more nuanced understanding of the asymmetric climate response to overshoot is essential for evaluating the feasibility and risks of overshoot-based mitigation strategies for a reality in which overshoot is necessary. However, there is currently no robust framework that would allow the decomposition and comprehensive quantification of all climate response features described herein. Here, we propose a set of idealized model experiments (Fig. A1), that align with CMIP7-relevant frameworks such as flat10MIP (Sanderson et al., 2025b), TIPMIP (Winkelmann et al., 2025), C4MIP and RCMIP (Romero-Prieto et al., 2026) and could guide systematic research to robustly capture the climate response features and irreversibility in climate processes. These experiments are based on cumulative CO₂ emissions trajectories and follow, in their core, the flat10MIP design philosophy (Sanderson et al., 2025b). They are complementary to the Tipping Points Modelling Intercomparison Project (TIPMIP) scenario design in temperature-space (Winkelmann et al., 2025). All these experiments can vary their duration, and the rate of positive and negative emissions (to test rate-dependence), and peak emissions (to test state-dependence). A careful selection and comparison of counterfactual experiments helps to isolate and quantify individual climate response effects.

The design (see Section S1; Fig. S1) includes: (E1 - esm-flatX-zec) baseline ZEC experiments establishing reference responses without overshoot; (E2 - esm-flatX-rev) overshoot-and-reversal experiments that assess climate outcomes under negative emissions; (E3 - esm-flatX-rev-target) cooling-phase branch experiments at specific landing climates (or cumulative emission levels) probing path-dependence and hysteresis; and (E4 - esm-flatX-rev-neg) idealized carbon removal experiments that isolate the intrinsic response to negative emissions without prior warming. These can be complemented by factorial (structural-switch) experiments that modify or enable/disable specific processes to attribute irreversibility and tipping behavior, with all experiments allowing systematic variation in emission rates, peak emissions, and durations to test rate- and state-dependence. these experiments in models across a wide spectrum of complexity and climate-component representation, including model intercomparison efforts. Where process modeling capability is lacking in more complex climate models, simpler mechanistic process models may help represent missing processes or constrain key climate feedbacks. If models could only afford running a single set of simulations, we would recommend prioritizing esm-flatX-rev experiments because of their relevance in comparison to real-world scenarios.

esm-flatX-zec (E1): are baseline ZEC experiments that define the reference climate response in the absence of overshoot. The base emission ramp-up follows a rate of X PgC per year to X*100 PgC of cumulative emissions (Sanderson et al., 2025b). Afterward, emissions are set to zero for as long as needed - ideally to equilibrium. These experiments establish the idealized long-term reference state against which overshoot responses can be evaluated. esm-flatX-zec experiments can be varied by emission rates and peak cumulative emissions.

esm-flatX-rev (E2): are overshoot experiments that branch off from esm-flatX-zec experiments. They include a deliberate exceedance of a target forcing or temperature level followed by a negative emissions phase. esm-flatX-rev experiments can be systematically varied in terms of emission ramp-up and ramp-down rates (including abrupt), peak overshoot magnitude and duration. In flat10MIP, such experiment design was missing, but is proposed as an extension as part of Phase 3 of the Reduced

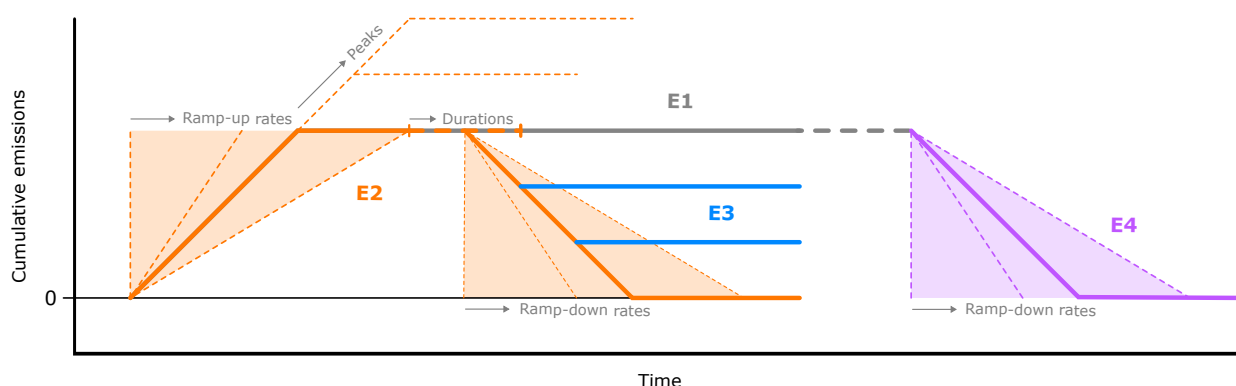


Figure A1. Experimental design strategy to quantify and decompose climatic mechanisms in response to overshoot. The modeling experiments include transient ZEC experiments (E1), classic overshoot experiments (E2), overshoot branch-off experiments (E3), and experiments that apply negative emissions from equilibrium climate states (E4). All experiments can additionally be conducted with structural-switch counterfactuals that enable/disable specific response features. Careful selection and comparison of different sets of experiments helps to isolate and quantify individual climate response effects.

Model Intercomparison Project (Romero-Prieto et al., 2026) and the C4MIP for CMIP7 protocol. Comparing experiments would allow assessment of the climate outcome from negative emissions following an overshoot, separated from a committed ZEC response. The “Climate Recovery” and “Climate Commitment” response archetypes would materialize in esm-flatX-zec and esm-flatX-rev. Cooling-driven and cooling rate-dependent effects would unfold in esm-flatX-rev experiments with varying rates of reversal and landing climates. The latter can be compared against esm-flatX-zec to delineate cooling-induced feedbacks.

esm-flatX-rev-target (E3): consists of cooling-phase branch-off experiments designed to diagnose path dependence and memory effects. At selected points of the cooling phase in the esm-flatX-rev experiments, the system is branched into stabilization pathways with emissions set to zero, e.g., to reach a target temperature level. By comparing branches taken at the same forcing level but different points in the trajectory, esm-flatX-rev-target experiments allow attribution of deviations to inertia-based hysteresis, state dependence, and cooling-specific irreversibility that cannot be inferred from peak conditions alone.

esm-flatX-neg (E4): are idealized carbon removal experiments initialized from equilibrium climate states. In these experiments, negative emissions equivalent to those applied during overshoot cooling phases are imposed without any prior warming history at varied emissions ramp-up and ramp-down rates (including abrupt), peak overshoot magnitude and duration. As a result, these experiments lack thermal and carbon-cycle inertia and therefore provide a clean separation of the dynamic responses to negative emissions. Simulations can be initialized from either a pre-industrial equilibrium, equilibrated higher-CO₂ climate states or long esm-flatX-zec experiments. esm-flatX-neg experiments are useful for isolating the intrinsic response to carbon



380 removal and identifying the role of accumulated inertia in overshoot pathways. They also allow a direct calculation of TCRR
asymmetry (Zickfeld et al., 2021; Chimuka and Zickfeld, 2026).

Factorial experiments: are structural-switch counterfactual experiments in which specific model components or feedbacks
are selectively modified or disabled and require (combinations of) climate models with targeted capabilities. E1–E4 experi-
ments cannot be used directly to decompose the residual term of Equation 1 (specifically response features C and D). However,
385 by comparing structurally modified simulations to their fully coupled counterparts applied across the E1–E4 experiments,
structural-switch experiments enable attribution of irreversibility and tipping behavior to particular processes, complementing
the trajectory-based counterfactuals provided by E1–E4 and addressing ‘Overcompensation’ and potential ‘Climate Runaway’
response archetypes.

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