https://doi.org/10.5194/egusphere-2025-3604
Preprint. Discussion started: 23 September 2025

The TIPMIP Earth system model experiment protocol: phase 1

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Preprint. Discussion started: 23 September 2025

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Abstract. We describe a new Earth system model (ESM) experiment protocol, as part of the international Tipping Points Modelling Intercomparison Project (TIPMIP) project. We propose this as a protocol for the Coupled Model Intercomparison Project 7 (CMIP7). The protocol requires ESMs to run in CO_2-emission mode, with atmospheric CO_2 a predicted variable. Forcing for the protocol consists solely of a constant emission of CO_2, based on each model's transient climate response to cumulative emissions of carbon dioxide (TCRE) value, to give a common global mean warming rate of 2 °C per century. This positive emission experiment is started from the pre-industrial state of a given model. When the ramp-up run first exceeds a specified level of global warming (2 °C and 4 °C) relative to the model's pre-industrial global mean surface air temperature (GMSAT), CO_2 emissions are set to zero and the positive emission run is branched into a zero-emission run. The zero-emission runs continue for 300 years. At 50 years into each zero-emission run, CO_2 emissions are set to the negative of the positive emission rate and the model run until GMSAT cools below the original pre-industrial value. Additionally, when the negative emission run started from global warming level (GWL) = 4 °C first drops below GWL = 2 °C, a zero-emission run is branched off this, completing the set of experiments. Using this protocol, we are able to control the rate of global warming and cooling across participating models. TIPMIP experiments will support a range of analyses, including; an assessment of abrupt/rapid Earth system change, the long-term response to zero CO_2 emissions, the response to negative CO_2 emissions, the efficacy of negative emissions in driving cooling, and the reversibility of Earth system change under a pathway of positive (warming), zero (stabilization), and negative (cooling) CO_2 emissions.

1 Introduction

We describe the Tier 1 experiment protocol to be followed by coupled Earth system models (ESMs) contributing to the Tipping Points Modelling Intercomparison Project (TIPMIP) (Winkelmann et al., 2025). This protocol (termed TIPMIP ESM Tier 1) has been designed as a simple (idealized) way to intercompare Earth system model (ESM) simulations forced sequentially by positive, zero, and negative carbon dioxide (CO_2) emissions. The protocol controls the rate of increase in global mean surface air temperature (GMSAT, referred to here as *the rate of global warming*) across ESMs during the positive emission phase, with a rate of ~2 °C per century chosen to approximate the observed global warming rate over the past ~50 years. The protocol ensures ESMs branch from positive to zero CO_2 emissions at the same global warming level (GWL), after the same rate and duration of global warming, with an approximate stabilization of global warming envisaged. Finally, models branch into common negative CO_2 emission pathways (CO_2 removed from the atmosphere) after a common time period under zero emissions.

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The protocol lends itself to addressing a number of important questions related to how the Earth system will respond to a global warming overshoot (i.e. temporary exceedance of a global warming target that is returned to at some later date), as well as to zero and negative CO_2 emissions. Areas of particular focus include (i) the risks and consequences of triggering Earth system tipping points, (ii) residual warming and global to regional Earth system change under long-term zero emissions at different GWLs i.e. the zero emission commitment (ZEC) (Jones et al., 2019), (iii) the reversibility of any induced changes following a negative CO_2 emission pathway, and (iv) the overall efficacy of negative CO_2 emissions in driving global cooling, including the regional patterns of this cooling. The protocol described in this paper assumes ESMs are run in CO_2-emission mode, meaning atmospheric CO_2 concentrations are a predicted model variable, dependent on the prescribed emissions and the response of each model's carbon cycle. Such an approach allows a more complete simulation and analysis of the coupled climate - carbon cycle response to positive, zero, and negative CO_2 emissions. An effort to develop an analogous experiment protocol for models run in (prescribed) CO_2-concentration mode is underway and will be reported in a subsequent paper. These ESM protocols will be complemented by related experiments in TIPMIP (Winkelmann et al., 2025) using standalone, domain-specific models such as land-vegetation models, ocean models, and ice sheet models that will be forced by output from the coupled ESM experiments.

2 Terminology and definitions

Tipping points occur in the Earth system where positive feedback loops are strong enough to induce self-sustained and often rapidly increasing change beyond a critical threshold, which drives the system from one preferred (equilibrium) state to another, with potential large-scale and negative consequences for human societies and natural ecosystems (Lenton et al., 2008; van Nes et al., 2016; Armstrong McKay et al., 2022; Lenton et al., 2023). The tipping point is the critical level of forcing (for example, CO_2 emissions, or deforested area) that initiates the tipping dynamics, (e.g. maintained melt leading to collapse of (parts of) an ice sheet). Tipping can also be induced when the rate of change of forcing exceeds a critical value, or stochastic internal variability leads to the initiation of nonlinear positive feedbacks ('rate-induced' and 'noise-induced' tipping, (Chapman et al., 2024)). The nonlinear nature of the tipping process has two important consequences: (i) the ensuing change is often abrupt with respect to the normal forcing of the system and/or rapid with respect to the typical timescales of the system experiencing the tip, and (ii) the change is often associated with a strong hysteresis, i.e. is practically irreversible, at least on societally relevant timescales. For example, if, after a warming overshoot, much colder temperatures are required to regrow an ice sheet to its pre-tip size than the temperatures that led to its collapse (Garbe et al., 2020). Abruptness and irreversibility are often consequences of the strong positive feedback loops but not necessarily a defining criterion for a tipping point. More details on the definitions and associated key terminology related to tipping points can be found in the recent TIPMIP overview paper (Winkelmann et al., 2025, e.g. see their Box 1).

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The TIPMIP ESM Tier 1 experiments focus on four primary "tipping elements" of the biophysical Earth system that have been shown to potentially exhibit tipping (or abrupt change) behaviour: (i) the Atlantic Meridional Overturning Circulation (AMOC), (ii) Greenland and Antarctic ice sheets, (iii) boreal and tropical forests, and (iv) (ground) permafrost. In addition, the TIPMIP experiments enable analysis of a wide range of other system responses beyond this shortlist, including, but not limited to, the North Atlantic subpolar gyre (SPG), sea ice systems, and modes of climate variability.

Previous theoretical (Stommel, 1961; Rooth et al., 1982) and modelling work (Swingedouw et al., 2007; Jackson et al., 2015; Liu et al., 2020) has demonstrated the capacity for, and consequences of, a collapse of the AMOC. Using paleo-observations and modern sea surface temperature observations, Caesar et al. (2018, 2021) suggest the AMOC may have already entered a weakening phase, although significant uncertainty remains regarding the robustness and strength of such a weakening signal in in-situ observations (e.g. Chen and Tung, 2018; Fraser and Cunningham, 2021; Killbourne et al., 2022). Model projections also show a large spread in the future AMOC evolution, with the global warming level at which tipping may occur not well-constrained (Ben Yami et al., 2024). Similar modelling and analysis efforts indicate susceptibility of the Greenland (Nöel et al., 2021; Gregory et al., 2020; Robinson, et al., 2012), East Antarctic, and West Antarctic ice sheets and sub-glacial basins (Feldmann and Levermann, 2015; Garbe et al., 2020; van Breedman et al., 2020) to irreversible decline beyond certain thresholds. Again, the thresholds for such behaviour are not well-constrained and thus formulating robust policy advice is difficult (Armstrong-McKay et al., 2022). Polar amplification has led to significant Arctic warming, more than twice as fast as the global average, as evidenced by rapid sea-ice loss (Taylor et al., 2022). Model projections indicate the first ice-free day in the Arctic could occur before 2030 (Heuzé and Jahn, 2024), with the potential to trigger tipping of multi-stressors affecting the marine ecosystem (Myksvoll et al., 2023; Heinze et al., 2021).

Dynamic global vegetation models (DGVMs), employed in coupled ESMs, have long demonstrated the capacity for rapid Amazon dieback (Cox et al., 2000; Good et al., 2011; Parry et al., 2022). A mounting body of work suggests the possibility of both climate and deforestation induced tipping, not only in the Amazon (Boers et al., 2017; Drijfhout et al., 2015; Lovejoy and Nobre, 2018), but also the boreal forest (Booth et al., 2012; Gerten et al., 2013; Koven et al., 2013). Similar modelling efforts show the potential susceptibility of permafrost systems to rapid, potentially irreversible change (Lenton et al., 2012), but stress that continued loss of permafrost with incremental warming means there is likely no "safe" level of warming for permafrost (Nitzbon et al., 2024). Furthermore, the trajectory of warming stabilization, characterized by the intensity and duration of warming overshoot, may lead to multiple steady states with distinct characteristics of high northern latitude soils, including carbon concentrations and fluxes, with potentially long-lasting (century or longer) effects after warming stabilization (de Vrese and Brovkin, 2021).

In the aforementioned systems, considerable uncertainties remain around critical forcing thresholds necessary to induce tipping, in particular the magnitude and duration of change (e.g. warming), (Ritchie et al., 2024; Stocker and Schmittner, 1997).

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While there are increasing efforts to study tipping dynamics in these systems in offline, domain-specific models (Naughten et al., 2023; Bochow and Boers, 2023; Garbe et al., 2020), relatively few attempts have been made to investigate the potential for tipping using fully coupled Earth system models, where dynamic feedbacks between Earth system components are explicitly modelled. While offline models are computationally less expensive, and in some cases offer more comprehensive treatment of individual tipping element dynamics, fully coupled ESMs are more likely to capture interactions between the phenomena at risk of tipping, as well as processes driving (or stabilizing) such a tipping risk. Coupled ESMs are also more suitable for investigating interactions between tipping elements (i.e. the risk of tipping cascades) and the broader climatic, environmental, and socio-economic consequences of tipping events (Wunderling et al., 2022; Franzke et al., 2022; Klose et al., 2020).

While the TIPMIP ESM Tier 1 protocol is focussed on coupled Earth system models, output from simulations following the protocol will also be used across TIPMIP to force domain-specific models (e.g. ice-, ocean-, and land-only models) to study in detail domain-specific processes controlling the potential for tipping in these systems.

3 Experimental design: Tier 1 experiments

In this section we describe in detail the experiment protocol to be followed by contributing models. All experiments are to be run in CO_2-emission mode (i.e. full simulated carbon cycle with prognostic atmospheric CO_2). The foundation of the protocol is a pre-industrial control simulation (esm_piControl). Once the esm_piControl is deemed sufficiently stable (defined by individual modelling groups, but likely requiring a minimum of a few hundred years integration) a positive CO_2 -emission (*ramp-up*) simulation is branched from the esm_piControl, with initial conditions taken from the esm_piControl on January 1st of the selected year A. The ramp-up is forced by a positive global mean CO_2 emission rate of X GtC yr^{-1} (equivalently X PgC yr^{-1}) where X is diagnosed from the model's TCRE (the transient climate response to cumulative emissions of carbon dioxide, Allen et al., 2009) to give a global mean surface air temperature (GMSAT) warming rate of 2 °C per century. We suggest using the method of Arora et al. (2020) to calculate model TCRE value, specifically equation 21 and the averaging timescales suggested therein. As an example, assuming a model TCRE of 2.5 °C per 1000 PgC, to realize a global warming rate of 2 °C per century implies a carbon emission rate of (2.0/2.5) x 1000 PgC = 800 PgC per century or 8 PgC yr^{-1}. If necessary, this approach can be slightly modified (i.e. TCRE values slightly adjusted) to ensure a 2 °C per century warming rate. While we do not want to be overly stringent, we recommend groups aim for a global warming rate of +2 °C +/- 0.1 °C for the first century of the positive emission run. As the ramp-up run reaches higher warming levels there is a greater risk that warming rates in some models deviate from the target rate. With respect to the geographical pattern of the positive CO_2 emissions, we suggest emitting with a spatial pattern that mirrors that used for the CMIP6 historical CO_2 emissions (for example the pattern of emissions for the final year of the CMIP6 historical period (2014)), scaled to give the TCRE-based

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emission rate needed, though given the long lifetime of well-mixed atmospheric CO_2, the spatial pattern of emissions is likely of secondary importance.

Apart from the introduction of positive CO_2 emissions, everything else in the ramp-up is unchanged from the esm_piControl set up. The esm_piControl run should be extended for as long as required to parallel the longest ramp-up -> zero-emission -> ramp-down -> zero-emission run employed in the protocol. Details of these, and the recommended length of the esm_piControl, are provided below in Table 1.

When GMSAT in the ramp-up run first exceeds a value 2 °C warmer than the esm_piControl GMSAT (i.e. GWL = 2 °C), CO_2 emissions are set to zero and a *zero-emission* (ZE) run is branched off the ramp-up. The start date of the ZE run is defined by comparing a 31-year (centred) mean GMSAT, for each year of the ramp-up, to the 31-year mean GMSAT centred on year A in the esm_piControl from which the ramp-up started. The ZE run start date is set to January 1st of the year directly after the first year GWL = 2 °C is diagnosed. The ZE simulation is run with CO_2 emissions set to zero for a minimum of 300 years. 50 years into the ZE run (i.e. January 1st of year 51 of the ZE run), a *ramp-down* run is branched, with CO_2 emissions set to minus the value of the ramp-up run (i.e. -X GtC yr^{-1}). The spatial pattern of negative emissions we leave to each modelling group to decide on, with two extreme options being (i) a negative mirror image of the pattern of positive emissions in the ramp-up or (ii) a spatially uniform pattern. This ramp-down run is continued until its 31-year mean GMSAT is less than the original 31-year mean GMSAT centred on year A in the esm_piControl from which the original ramp-up started. At this point the ramp-down run can be stopped. Figure 1 illustrates this *esm_piControl -> ramp-up -> zero-emission -> ramp-down* procedure.

The original ramp-up run is continued until its GMSAT first exceeds 4 °C warmer than the esm_piControl, calculated in the same way as for GWL = 2 °C. At GWL = 4 °C a second ZE run is branched off the ramp-up and run for 300 years. As for the ZE run at GWL = 2 °C, 50 years into the ZE run at GWL = 4 °C a X GtC yr^{-1} negative emission ramp-down is started and run until its GMSAT value is less than the original esm_piControl value (calculated as described above for the GWL = 2 °C ramp-down). Finally, when the 31-year running mean GMSAT in the ramp-down run started from GWL = 4 °C first becomes colder than 2 °C above the original esm_piControl GMSAT, a second ZE run at GWL = 2 °C is branched off the GWL = 4 °C ramp-down. This procedure is shown visually in Fig. 1. Table 1 summarises the various steps in the TIPMIP Tier 1 ESM protocol.

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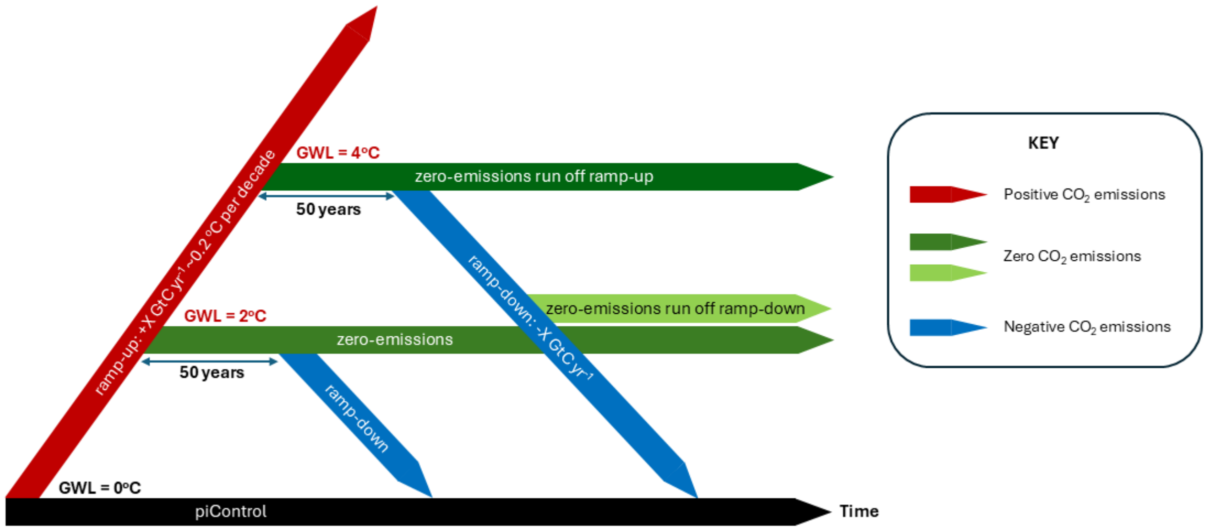

205 **Figure 1: Schematic of the TIPMIP ESM phase 1, tier 1 experiment protocol**

Simulation	GWL start value	CO_2 emission GtC yr^{-1}	Run length	GWL end value
esm_piControl	0 °C	0.0	~700 years or as required to parallel experiments below	0 °C
ramp-up	0 °C	+X	until GWL > 4 °C ~200 years	> 4 °C
zero-emission (from ramp-up)	2 °C in ramp-up	0.0	300 years	undefined
ramp-down	50 y into 2 °C ZE	-X	until GWL < 0 °C	0 °C
zero-emission (from ramp-up)	4 °C in ramp-up	0.0	300 years	undefined
ramp-down	50 y into 4 °C ZE	-X	until GWL < 0 °C	0 °C
zero-emission (from ramp-down)	2 °C in ramp-down	0.0	300 years	undefined

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Table 1: List of runs forming the TIPMIP ESM phase 1, tier 1 experiment protocol.

3.1 Caveats to the experiment protocol

The main positive aspect of the TIPMIP protocol is its simplicity, with only CO_2 emissions (positive, zero, and negative) needing to be prescribed. Using emission rates derived from each model's TCRE, we aim to control the GMSAT warming rate to be common across models during the ramp-up, and ensure models switch to zero-emissions at the same global warming level, relative to their pre-industrial temperatures, after the same rate and duration of global warming. These assumptions rest on an assumed linearity of TCRE across global warming levels (and increasing cumulative CO_2 emissions) in the ramp-up. Put another way, we expect a unit emission of CO_2 (X GtC) to cause the same unit increase in global mean surface air temperature (Y °C), whether the unit emission happens early in a ramp-up run (when accumulated CO_2 emissions and induced warming are relatively small) or later in the same run (when accumulated CO_2 emissions are larger and induced warming is also larger). This assumption of linearity appears very accurate at lower warming levels (modest accumulated CO_2 emissions) but becomes less accurate at higher warming levels (greater accumulated CO_2 emissions), resulting in a slight deviation in some models in the rate of warming away from the target 2 °C per century at higher GWLs (Krasting et al., 2014). The degree to which this deviation complicates our analysis will be one important outcome of the first round of multi-model simulations and will inform further development of the protocol. While any global warming rate could, in principle, be realized (using different CO_2 emission rates linked to each model's TCRE), we chose 2 °C per century as this is the approximate rate of observed GMSAT increase over the past ~50 years.

We do not explicitly control the evolution of GMSAT in the zero-emission runs. We expect changes in GMSAT during these phases (the zero-emission commitment (Jones et al., 2019) to be close to zero (MacDougall et al., 2020). Each model's ZEC is an emergent property - which may depend on global warming level - following a common experiment protocol. While we force the ramp-down runs to have a mirror image, negative emission of the ramp-up, this does not guarantee each model will cool at -2 °C per century. The realized cooling rate in each model will depend on how its carbon cycle, atmospheric CO_2 concentrations, and climate respond under prescribed negative emissions. We might expect a near mirror image ramp-down global cooling, but this too will be an emergent property of each model, likely related to its ZEC (Koven et al., 2023).

While the simplicity of our protocol is a strong positive, it is also its main weakness. This is notably because we ignore other important anthropogenic forcings of the Earth system. In particular, the Tier 1 protocol does not include anthropogenic emissions of aerosol and aerosol precursors. The protocol does include natural aerosols (as simulated in each individual model esm_piControl), including any responses of natural aerosols to warming/cooling experienced along the ramp-up, zero-emission, ramp-down pathway. Anthropogenic aerosols have provided an important (time varying, spatially heterogeneous) negative radiative forcing during the historical period (1850 to present-day), balancing a significant fraction of the historical

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warming due to anthropogenic greenhouse gas (GHG) emissions (Gillet et al., 2021; Smith and Forster, 2021). Anthropogenic aerosol emissions also vary significantly across different future emission scenarios, for instance in the CMIP6 Shared Socioeconomic Pathways (SSPs) (Gidden et al., 2019). Due to their short atmospheric lifetime (days to weeks) and strong interaction with low-level clouds (Williams et al., 2021; Fons et al., 2023) anthropogenic aerosol forcing has a specific geographical structure (Wilcox et al., 2023). Over the historical past, aerosol induced cooling is far greater in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH), while GHG forcing is more homogeneous. As a consequence, the total historical anthropogenic radiative forcing at the top of atmosphere (TOA) has a distinct NH to SH gradient. This gradient, as well as the detailed spatial structure of aerosol forcing, will not be captured in our protocol. This may have important consequences for simulated AMOC changes (Menary et al., 2020).

A second important omission is human land-use, which is not included in our protocol. Human land use has provided a negative forcing of the Earth system over the historical period. For example, in the HadGEM3-GC3.1 contribution to CMIP6 human land-use forcing was -0.11 W m^{-2}, ~6 % of the total historical anthropogenic forcing in that model (Andrews et al., 2019). At regional scales, particularly with respect to tropical forests and their resilience, human land use (i.e. deforestation) plays a critical role (Flores et al., 2024), potentially of similar importance to global climate change (da Cruz et al., 2021, Boulton et al., 2022). For potential tipping of forest ecosystems (particularly the Amazon) our experiment protocol therefore neglects an important driver. Introduction of human land-use and anthropogenic aerosol are high priorities for a tier 2 set of experiments, but require careful testing before they can be included, as our aim will still be to retain as much commonality as possible in global warming pathways across contributing models. The TIPMIP Tier 1 experiments will be used to drive (global and regional) offline land-vegetation models. An initial assessment of the role of human land use change, at different GWLs, can be made in these offline models, although ultimately this needs to be introduced back into the coupled ESM protocol so feedbacks between land-use change, regional climate, and forest response can be captured (Wu et al., 2021; Cano et al., 2022).

Our protocol also does not consider non-CO_2 anthropogenic GHG emissions, such as methane (CH_4), ozone (O_3), nitrous oxide (N_2O) or chloroflurocarbons (CFCs and HCFCs). While these are important forcers, for example when combined giving an historical radiative forcing ~75 % of that due to anthropogenic CO_2 emissions (Chapter 7, IPCC: Climate Change 2021 WGI, 2023), their lifetime, horizontal distribution, and impact primarily on the longwave part of the Earth's radiation budget, suggest to a first order their forcing can be mimicked by an equivalent CO_2 emission. Omission of anthropogenic CFCs and HCFCs also means there will be no stratospheric ozone depletion (Solomon, 2019) in our experiments.

Because our protocol is forced solely by CO_2 emissions, with no aerosol or other well-mixed greenhouse gas (WGHG) emissions and associated negative radiative forcing included, it is very likely that when the idealized runs reach GWL = 2 °C and 4 °C (the start of the zero emission runs) they will have experienced a larger cumulative emission of CO_2 than equivalent multi-gas and land-use scenarios at the same GWL. This is primarily because the positive radiative forcing arising from non-

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CO_2 WGHGs (e.g. methane, ozone, nitrous oxide etc) in the multi-gas scenarios is being achieved (in a warming sense) by CO_2 emissions in the idealized runs. This is partially offset by not including aerosol (negative radiative forcing). One consequence of this is that the ocean dissolved inorganic content (DIC) will be greater in the idealized runs and ocean pH lower. These differences need to be considered when analysing marine ecosystem responses.

The Tier 1 protocol requests only one member per model for each leg of the protocol. This is to maximise the number of modelling groups able to contribute. In some cases, tipping events are expected to be rare occurrences. Hence, a large ensemble of runs would help in sampling such events, including potential stochastic forcing of a tipping event (Romanou et al., 2023), while also helping identify when, and under what conditions, in our simulations a tipping event is more likely to occur. This can be partially addressed by the multi-model aspect of the protocol, with 12 ESMs already expressing an interest to run these experiments. Nevertheless, we recognize the need for more ensemble members. For instance, a bifurcation in the AMOC has been shown to exist in one ESM and could therefore have implications for the timing and reversibility of AMOC-related tipping events (Romanou et al., 2023). It is for this reason we encourage groups to consider running additional ensemble members (started from different time points in their esm_piControl) in the potential extensions to Tier 1. Similarly, the Tier 1 protocol asks for the zero-emission runs to be a minimum of 300 years in length. This is sufficient for investigating a number of Earth system responses, but for some of the slower Earth system components (e.g. ice sheets or the deep ocean) significantly longer runs are required. We therefore encourage groups to extend their zero-emission runs to 500 years or longer, in the potential extensions to the Tier 1 protocol.

3.2 Potential extensions to the Tier 1 protocol: Tier 2 experiments

There are a number of desirable (voluntary) extensions to the Tier 1 protocol, that we encourage modelling groups to consider running if resources allow. These include:

1. Extend the two ZE runs at GWL = 2 °C and 4° C (started from the ramp-up) and the one ZE run at GWL = 2 °C, branched off the ramp-down from GWL = 4 °C, to 500 years each (or as long as possible).

2. When the two ramp-down runs (started respectively from (i) GWL = 2 °C and (ii) GWL = 4 °C) first pass GWL = 0 °C (i.e. pre-industrial GMSAT), branch zero-emission (ZE) runs at GWL = 0 °C and run these for 500 years (or longer).

3. Extend the original esm_piControl so it is sufficiently long to act as a reference for the new ZE runs proposed under points 1 and 2.

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4. Increase the ensemble size of all legs of Tier 1. e.g. by starting new ramp-ups and subsequent ZE and ramp-down legs of the protocol, as additional ensemble members branched from the esm_piControl. We leave groups to decide how they add additional members but suggest a minimum of 30 years separation in the esm_piControl between starting new ramp-up runs.

5. In addition to ZE runs branched off the ramp-up runs at GWL = 2 °C and 4 °C, also perform ZE runs sampling GWL = 1.5 °C, 3 °C and 5 °C, ideally for a minimum of 500 years each.

6. In addition to the -X GtC yr^{-1} negative emission runs starting 50 years into each ZE run, start identical negative emission runs later into the ZE run (after 200 years is recommended).

7. Repeat negative emission runs from the same ZE start points, but rather sample negative emission rates equal to 50 % and 25 % of the original -X GtC yr^{-1}.

3.3 A reduced set of Tier 1 experiments: Tier1_reduced

To maximize the number of models contributing to TIPMIP, we have developed a reduced set of Tier 1 experiments. While we encourage modelling groups to run the full set of experiments whenever possible, groups will be able to participate in Tier 1 by realising the reduced set of runs:

- An *esm_piControl* for 300 years
- One *ramp-up* run at X GtC yr^{-1} to GWL = 2 °C
- One *zero-emission (ZE)* run at GWL = 2 °C for 200 years
- One ramp-down run (started 50 years into the ZE run at GWL = 2 °C), run back to GWL < pre-industrial.

3.4 Links to other CMIP7 model intercomparison projects (MIPs)

The TIPMIP ramp-up and zero-emission simulations have similarities with the constant emission and zero- and negative-emission simulations planned in CMIP7 flat10MIP (Sanderson et al., 2024). A key difference between the two sets of experiments is that the TIPMIP protocol aims to enforce approximate commonality across models in the temporal evolution of GMSAT; i.e. similar warming rates and duration of warming in the positive emission runs, zero emission runs started at the same GWLs after the same amount of warming, and potentially similar cooling rates in the negative emission runs, accepting that the amount of CO_2 emitted into each model will necessarily be different to realize this. In flat10MIP, commonality in CO_2 emissions is enforced across models, while inter-model variability in the evolution of GMSAT is accepted. While there is some commonality in the TIPMIP and flat10MIP experiments, there are sufficient differences and complementarity to make collaboration across the MIPs productive. The flat10 set of experiments (ramp-up, zero-emission, and ramp-down) are

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deliberately minimalist in design to reduce the demand on modelling centres. From these experiments TCRE can be measured for each ESM under a common forcing (uniform emissions rate of +10 GtC yr^{-1} for all models). TCRE, defined as the warming after this emission rate for 100 years, is a quantity required for the IPCC AR7 assessment, as is ZEC, defined also as the continued change in GMSAT during the esm-flat10-zec simulation. TIPMIP simulations are more extensive and naturally follow on from flat10 (which can be used to derive the TCRE-based emission rate to achieve a global warming of 2 °C per century). They are designed to explore in more detail model responses, following close-to-uniform warming rates and sampling a number of common global warming levels. The state-dependence of ZEC and response to negative emissions is a particularly useful and unique analysis offered by the TIPMIP simulations

Earth system change and regional patterns of change seen in the TIPMIP experiments can also be compared with results from ScenarioMIP (O'Neill et al., 2016; van Vuuren et al., 2025) and CMIP7 DECK (diagnostic, evaluation and characterization of klima) experiments (e.g. 1pctCO_2 and abrupt 4xCO_2 runs, Dunne et al., 2025) at similar transient global warming levels. This will provide information on the impact of staying long-term at a given GWL compared to transiently passing through it. Attention will need to be paid to the fact the TIPMIP simulations are forced solely by variable CO_2-emissions, with other important anthropogenic drivers left at their pre-industrial values. ScenarioMIP forcing is a multi-gas mix, including time varying aerosol emissions and human land-use. The latter, while more realistic, is more difficult to achieve commonality of GMSAT behaviour across models, which is a primary aim of the TIPMIP protocol.

A recent multi-model initiative, AERA-MIP (Silvy et al., 2024), provides 1.5 °C and 2.0 °C stabilization simulations that account for all anthropogenic drivers. This approach utilizes the adaptive emission reduction approach (AERA, Terhaar et al., 2022) to produce temperature stabilization simulations for two GWLs, following realistic historical forcing trajectories. TIPMIP simulations can be compared with AERA-MIP results to explore, for instance, the impact of non-CO_2 radiative forcing agents on the spatial patterns of climate change under stabilized GMSAT conditions, in particular at GWL = 2 °C, which are sampled both in AERA-MIP and TIPMIP.

The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP, Keller et al., 2018) explores the potential for, and impacts of, CDR deployment. CDRMIP addresses questions concerning reversibility, the response of the Earth system to atmospheric CO_2 removal (negative CO_2 emissions), and the CDR potential of proposed schemes, such as afforestation/reforestation and ocean alkalinization. The combination of idealized ramp-up (1% CO_2 yr^{-1}) and ramp-down (-1% CO_2 yr^{-1}) concentration experiments in CMIP6-CDRMIP represent abrupt and non-linear atmospheric CO_2 rates of change, which could compromise the carbon cycle climate feedback estimates (Schwinger et al., 2018; Asaadi et al., 2024). The emission-driven experimental design in TIPMIP ensures models follow a smoother trajectory than the artificial discontinuity imposed by a sudden jump from +1 % to -1 % rate of change of atmospheric CO_2. TIPMIP coordinators are in touch with the CDRMIP developers for CMIP7 to ensure commonality of approaches and sharing of data to support both MIPs.

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We have dubbed the TIPMIP Tier 1 protocol "*see what happens*" experiments. By this we mean the runs do not include any external interventions or forcings to ensure a tipping event occurs. There is a widespread feeling that ESMs may be designed (explicitly or unconsciously) to be overly stable with respect to tipping events (Rahmstorf, 2024; Valdes, 2011). This means there is a risk only a small number of tipping events occur in our Tier 1 ensemble. A natural extension to the TIPMIP ESM Tier 1 protocol, in particular using the zero-emission runs at GWL = 2 °C and 4 °C, is to deliberately induce a tipping event in these simulations. This has the advantage of knowing, in advance, the climate state at which the tip occurs and automatically having a non-tipping counterfactual run sampling the same climate state as the tipping run. Tips can be induced by prescribing external forcing terms or by making targeted modifications to key model parameterizations to increase the sensitivity of a given system to climate forcing. Such *forced tip "make it happen"* experiments will be developed in collaboration with the domain-specific activities in TIPMIP, as well as TIPMIP-WHATIF (Winkelmann et al., 2025) to ensure widespread utility of the resulting experiments across the TIPMIP project.

3.5 Diagnostics for all phase 1 experiments

The data request for TIPMIP starts from the data request for the *esm-historical* experiment in CMIP6. In a first step the number of requested variables was reduced to only include variables that all of 3 sample ESMs were able to produce, assuming these provide a reasonable subset of CMIP6 models. The list was further reduced by excluding most variables at sub-daily frequencies. TIPMIP experiments cover several centuries, and the amount of data would become impractical if sub-daily data, especially on multiple levels, were to be saved. The reduced list was then passed to TIPMIP domain experts for inspection, which resulted in some additional variables that were considered important for analysing domain specific tipping points and their precursors. TIPMIP ESM output will be used as forcing data for offline, domain-specific models in TIPMIP. We also anchored our diagnostic list with the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Frieler et al., 2024) to ensure data saved can be used to force sectorial impact models. All diagnostics follow CMIP6plus CMOR (climate model output rewriter) protocols. CMIP7 protocols will be used once they are fully established.

3.6 File naming conventions

TIPMIP comprises a number of zero emission (ZE) simulations at specific GWLs, as well as positive CO_2-emission (ramp-up) and negative CO_2-emission (ramp-down) experiments that link one warming level with another. A ZE experiment branching directly off a ramp-up experiment will therefore be different from another ZE experiment, at the same GWL, branching off a ramp-down experiment itself started from a higher GWL value. To distinguish between these two experiments, we propose a naming convention that allows us to construct experiment names by using short blocks describing each experiment phase and then adding these blocks together to form unique *experiment_ids* for each possible experiment. The building blocks and example experiment file names are listed below in Tables 2 and 3

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Building Block	Description
upXpY	Ramp-up simulation, following approximately a warming rate of XpY °C per century. XpY is given to one decimal place with the decimal point replaced by "p", e.g. 2p0 equates to 2.0 °C per century, up indicates positive emissions (ramp-up).
dnXpY	Ramp-down simulation, using negative emissions of the same magnitude as those used in upXpY. Note in these experiments the actual cooling rate may deviate from -XpY °C per century, dn indicates negative emissions (ramp-down).
gwlXpY	Zero-emission simulation that starts when GMSAT is XpY °C warmer than the relevant pre-industrial control GMSAT, gwl signifies the GWL of each ZE run.
Ny	Length in years that a zero-emission (gwlXpY) experiment has run before a ramp-down experiment is branched off it. N indicates the number of years.

Table 2: Building blocks of the naming schemes for creating experiment_id's.

410 The building blocks are combined to identify the full history of a given experiment. By using these building blocks, it is possible to distinguish ZE experiments at different GWLs that have started directly off a ramp-up run, from those that have started after a ramp-up, ZE run at a higher GWL, and ramp-down back to the GWL of the ZE run in question, or distinguish between experiments with different length ZE runs before a ramp-down run is started. Table 3 lists the *experiment_id* and *experiment* metadata for the Tier 1 experiments. The proposed extensions to the Tier 1 protocol, as well as future TIPMIP Tier
415 2 experiments will follow the same naming convention.

experiment_id	Experiment	Description
esm-up2p0	Ramp up run with constant CO_2 emissions giving a warming of ~ 2 °C per century	Ramp-up run branching off the esm-piControl
esm-up2p0-gwl2p0	Zero emission run starting at GWL = 2 °C, branching off esm-up2p0	GWL = 2 °C experiment, branching off the ramp-up when GMSAT is 2 °C warmer than pre-industrial.
esm-up2p0-gwl4p0	Zero emission run starting at global GWL = 4 °C, branching off esm-up2p0	GWL = 4 °C experiment, branching off the ramp-up when GMSAT is 4 °C warmer than pre-industrial.

esm-up2p0-gwl2p0-50y-dn2p0	Ramp down simulation with CO_2 emissions that are the negative of those used in esm-up2p0 (-X), branching off esm-up2p0-gwl2p0 after 50 years.	Ramp-down experiment, starting 50 years into the zero-emission run at GWL = 2 °C.
esm-up2p0-gwl4p0-50y-dn2p0	Ramp down simulation with CO_2 emissions that are the negative of those used in esm-up2p0 (-X), branching off esm-up2p0-gwl4p0 after 50 years.	Ramp-down experiment, starting 50 years into the zero-emission run at GWL = 4 °C.
esm-up2p0-gwl4p0-50y-dn2p0-gwl2p0	Zero emission run starting at GWL = 2 °C branching off esm-up2p0-gwl4p0-50y-dn2p0	GWL = 2 °C experiment, branching off a ramp-down run that was started from a ZE run at GWL = 4 °C

Table 3: *experiment_id* and *experiment* attribute for the TIPMIP ESM phase-1 experiments. The prefix "esm-" follows CMIP6 standards and indicates that these are CO_2 emission driven experiments.

4 Science questions to be addressed

4.1 Tipping points and abrupt change

Tipping of Earth system elements is often considered a low-likelihood high-risk event that may result in severe, even catastrophic, consequences for ecosystems, biodiversity, and society. In recent years there has been increasing evidence from past changes, observational records, and models that several parts of the Earth system are already undergoing rapid, potentially irreversible change (Lenton et al., 2008, 2019), which may lead to crossing of tipping points. Components of the Earth system at risk of tipping include the West Antarctic and Greenland ice sheets, Amazon and some boreal forests, savanna and dryland ecosystems, coral reefs, the Atlantic Meridional Overturning Circulation (AMOC), the North Atlantic Subpolar Gyre (SPG), and ground permafrost. (e.g. Levermann and Winkelmann, 2016; Sgubin et al., 2017; Staal et al., 2020; Swingedouw et al., 2020, 2021; Chapter 9, IPCC, 2023; Armstrong McKay et al., 2022). Recent studies estimate that widespread, at least partly irreversible, ice mass loss from the West Antarctic ice sheet may be triggered when global warming levels range from 1 °C to 3 °C above pre-industrial levels (Golledge et al., 2017; Garbe et al., 2020; Reese et al., 2023). For the Greenland ice sheet, a critical threshold is estimated in the range 0.8 °C to 3 °C of global warming, with a best estimate of about 1.5 °C (van Breedam et al., 2020; Noël et al., 2021; Höning et al., 2023). The recent Global Tipping Points Report 2023 (Lenton et al., 2023) concludes that some Earth system tipping events are no longer high-impact, low-likelihood events, rather they are rapidly becoming high-impact, high-likelihood events.

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However large uncertainty still exists in these estimates. Many studies use a range of observational data including paleo-proxy records, in situ measurements, as well as atmosphere and ocean reanalysis data. Satellite remote sensing data, covering the past few decades, is playing an increasing role in analysing tipping dynamics across scales (Swingedouw et al., 2020; Lenton et al., 2024), because of its global coverage at fine temporal and spatial resolution. In situ observational data is often spatially too coarse, and satellite data temporally too short, to reliably detect early warning signals of large-scale tipping events. Earth system models offer global coverage at reasonable (but by no means sufficiently detailed) spatial resolution and can be integrated for multi-centuries. In principle at least, ESMs can therefore be used to investigate where, when, and how, tipping events are triggered (Romanou et al., 2023; van Westen et al., 2024a, 2024b), as well as how different tipping systems interact. Model studies so far have mostly been based on either a single model, and/or individual experiment design, with a focus on individual tipping elements (e.g., the North Atlantic Hosing Model Intercomparison Project (NAHosMIP) and AMOC, Jackson et al., 2023).

A key aim of the TIPMIP ESM protocol is to assess the risks and consequences of a range of tipping events using a common experiment protocol sampled by multiple ESMs. We aim to investigate the risk of tipping events as a function of different levels of (long-term) global warming, and if triggered, whether the ensuing changes are reversible (through global-scale cooling) on societally relevant timescales. Armstrong McKay et al. (2022) provide estimates of timescales and warming thresholds where Earth system tipping events become an increasing risk. In addition, Ritchie et al. (2021, 2024) stress both the peak global warming level (GWL), and the duration spent at a given GWL before cooling, are important determinants of the risk of triggering a tipping event. The TIPMIP Tier 1 protocol offers a (minimal) set of multi-model experiments to address such tipping risks at (i) two different GWLs, (ii) associated with the duration spent at that GWL, and (iii) the potential for reversibility as warming is reduced.

A number of studies have identified abrupt changes in ESMs (Drijfhout et al., 2015; Swingedouw et al., 2021), including stochastic collapse of the AMOC (Romanou et al., 2023), localized, rapid Amazon loss (Parry et al., 2022), and rapid, irreversible mass loss of the West Antarctic ice shelf (Naughten et al., 2023). In addition, van Westen et al. (2024a) show how an annually moderate, but cumulatively large, freshwater flux into the Atlantic in the CESM model can induce positive feedback driving a collapse of the AMOC, involving physically plausible and understandable mechanisms. They further highlight that such feedback is poorly represented in present-day models, including Community Earth System Model (CESM), due to large biases in simulated salinity fields. van Westen et al (2024b) extend this work to derive a fingerprint for AMOC collapse (based on surface ocean buoyancy characteristics in the North Atlantic), which they apply to an ensemble of CMIP6 projections, finding a greater than 50% likelihood the AMOC will pass a critical point for tipping during the 21st century following a middle-of-the-road emission scenario, with the consequent AMOC weakening taking longer to evolve. With respect to permafrost, recent studies emphasize the need to incorporate frozen soil thaw dynamics and associated carbon release into models to accurately estimate available carbon budgets (Natali et al., 2021; Turetsky et al., 2020). CMIP6 ESMs are

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capable of simulating gradual permafrost thaw, but lack the necessary resolution and process representation to capture the spatial heterogeneity of permafrost thaw dynamics, in particular related to abrupt thermokarst processes, and microbial activity determining proportions of permafrost carbon that decomposes into CO_2 versus CH_4. Quantifying the impact of these processes is essential for reducing uncertainties in potential permafrost tipping behaviour. Within the TIPMIP project (Winkelmann et al., 2025), the TIPMIP ESM experiments will provide forcing data necessary to drive the next generation of standalone models representing high northern latitude terrestrial processes and to refine estimates of annual permafrost thaw dynamics using the methodology of Burke et al. (2020), thereby improving predictions of permafrost carbon impacts and the potential for rapid loss of permafrost volume.

For many of the phenomena at risk of tipping (e.g. AMOC, SPG, Antarctic ice sheets, Amazon forest), ESMs exhibit significant biases in the representation of these phenomena (Li et al., 2021; McCarthy and Caesar, 2023). Biases are also evident in the key climate drivers of these phenomena (Mecking et al., 2017; Robson et al., 2022; Jensen et al., 2024), including the representation of extreme events that might push a system beyond its resilience limits (Romanou et al., 2025). An important requirement is therefore to assess the quality of the TIPMIP ESMs in simulating the phenomena of interest, the key climate controls of these phenomena (see for example, Sgubin et al., 2017; Swingedouw et al., 2021, for analysis examples related to the SPG), including those that control the risk (or not) of a phenomenon tipping. For this we will focus on established metrics and climate controls for each phenomenon, including statistical and physically based metrics (or fingerprints) that are considered robust indicators of a potential tip. In this respect, the development of robust observational constraint approaches (e.g. Portmann et al., 2025) is important, as is the need for a significant multi-model ensemble sampling the proposed experiments.

Once a tipping event is identified in a simulation, we will assess; (i) the mechanisms underpinning the event, comparing the key driving processes of the tip across the multi-model ensemble (MME) sampling similar climatic conditions (e.g. GWLs) and, where possible, assess the plausibility of the identified tipping dynamics against observations and/or more detailed models; (ii) whether there are early warning signals (statistical and/or physically-based) prior to the occurrence of the identified tip and then search for the occurrence of similar indicators across the MME; (iii) the broader consequences of any identified tip for the rest of the Earth system, considering both geographically remote impacts (Ritchie et al., 2020) and interactions between different components of the Earth system (Klose et al., 2024). Systems at risk of tipping have the potential to interact (i.e. if one regional system tips, cascading teleconnections can influence the risk of a tip in another remote system). Many interactions are of a destabilising nature, implying the possibility of cascading transitions under global warming (Wunderling et al., 2024), although examples of stabilizing interactions do exist (Nian et al., 2023). An ESM dynamically couples different Earth system processes. The TIPMIP protocol will therefore allow us to investigate potential tipping point interactions, at the process level and across models, enabling a robust quantification of any interactions and possible cascades, based on state-of-

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the-art ESMs. Furthermore, by systematically screening the experiments for abrupt changes, it may be that previously unknown tipping point risks are identified.

4.2 Long-term change under zero-emissions at different global warming levels

The Paris Agreement aims to limit global warming to below 2 ˚C (and pursue efforts to limit warming to 1.5 ˚C) compared to pre-industrial temperatures. However, GMSAT has already increased by almost 1.5 ˚C and cumulative GHG emissions continue to increase (Friedlingstein et al., 2025). It is therefore unclear when, and at what global warming level, temperatures (and associated emissions) might be stabilized in the future. It is also unclear if, how, and how rapidly, global temperatures can be reduced, for example through CO_2 removal (CDR) and negative CO_2 emissions. It is possible global temperatures remain significantly above present-day values for a long period (decades or even centuries) before any significant cooling occurs. It is therefore urgent to understand how the Earth system will respond, at global and regional scales, to different levels of long-term warming stabilization that eventually arise from net-zero emissions (King et al., 2021; King et al., 2024; Chamberlain et al., 2024; Silvy et al., 2024). Such analysis requires long-term, zero-emission simulations with ESMs, at different GWLs. The TIPMIP Tier 1 protocol requests at least 300-year (preferably 500-year) zero-emission simulations at GWLs of 2 and 4 °C. This is an important multi-model data set for assessing the long-term consequences of stabilizing the Earth system at these GWLs.

Slow processes such as melting of ice sheets, ocean warming and associated thermal expansion, ocean circulation and carbon cycle changes, will continue to evolve long after net-zero emissions and warming is stabilized, leading to continued sea level rise, ocean deoxygenation and acidification, changes in ocean carbon uptake, and regional climate changes, all for many centuries (e.g. Frölicher and Joos, 2010; Bonan et al., 2022; Lacroix et al., 2024; Morée et al., 2025). Paleo evidence suggests a committed global sea level rise of around two meters per degree of global warming on millennial time scales (Levermann et al., 2013; Pattyn et al., 20218. Continuous freshwater input to the ocean, from melting land ice, will also have long-term impacts on ocean circulation (Swingedouw et al., 2007). Even after such freshwater forcing has terminated the ocean may require centuries to fully adjust (Hu et al., 2008). Sensitivity experiments with and without ocean circulation response to climate change show the importance of ocean circulation for the spatial structure of regional climate change (Winton et al., 2013). As long as the ocean is still adjusting, feedbacks onto other components of the Earth system, expressed through changes in marine heat and carbon fluxes (DeVries et al., 2017; Rugenstein et al., 2020), have the potential to impact patterns of regional climate change.

In addition to investigating the likelihood of tipping points at different GWLs, zero-emission (warming stabilization) simulations provide an opportunity to investigate incremental, long-term changes in the Earth system. Such incremental change, for example gradual temperature or precipitation changes, reduction of Arctic Sea ice, or gradual sea level rise, can

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lead to thresholds being exceeded that result in significant impacts on ecosystems and society, or even tipping of elements in these systems, such as abrupt shifts in vegetation (Wei et al., 2025), regime shift in marine primary productivity (Vasilakopoulos et al., 2017), biodiversity loss (Ureta et al., 2022) or permanent displacement of people (de France et al., 2017). Furthermore, gradual change in the mean climate can induce shifts in preferred modes of regional climate variability (Horton et al., 2015; Tamarin-Brodsky et al., 2020; Kim and An, 2024), with important consequences for extreme climate and weather events (Fischer et al., 2021; Wehrli et al., 2022). The TIPMIP protocol offers the possibility to study both incremental climate change and associated regional changes in variability and extreme events in a long-term, zero-emission MME starting from common GWLs.

While climate change is not yet one of the top drivers of biodiversity loss (Jaureguiberry et al., 2022), it is emerging as a threat to biodiversity, including decline in body condition (Bush et al., 2020), changes in phenology (Sgubin et al., 2018; Kubelka et al., 2022), shift of species poleward (Soultan et al., 2022) or to higher altitudes (Kubelka et al., 2022). Persistent and recurrent extreme temperature or precipitation events impact the ecology and habitat size of different disease vectors (Liu-Helmersson et al., 2014) and put stress on agriculture (Sgubin et al., 2019) and infrastructure. Past gradual changes in precipitation led to abrupt changes in vegetation types (Zhao et al., 2017). Output from the TIPMIP ESM experiments will be used to drive impact models in ISIMIP (Frieler et al., 2024) to investigate such risks in both the positive emission (ramp-up) experiments, the zero-emission runs, and (with respect to potential reversibility of impacts) in the negative emission (ramp-down) experiments.

There is increasing interest in understanding the long-term impacts of global change at specific GWLs (Silvy et al., 2024; King et al., 2024), to overcome uncertainty in the projected timing of future warming and address questions pertinent to the Paris Agreement. Most studies to date have been based on transient projections, analysing periods where global warming falls in an interval around a given target level (Lennard et al., 2018; Tebaldi et al., 2021; Swaminathan et al., 2022). These studies suffer from the fact that the transient climate at a certain warming level differs from the climate after a longer period (decades or more) at the same level. Such studies are also sensitive to the particular projection pathway chosen for analysis at a given warming level and show different results for earlier and later periods of the chosen time-interval. In many regions, this leads to substantial differences between the transient and the equilibrium climate at the same GWL (King et al., 2020, 2024; Lacroix et al., 2024). The long-term (300+ years) zero-emission simulations in TIPMIP will offer valuable insights into what a warmer world will look like if temperatures are stabilized close to a given GWL for multi-decadal or centennial time periods. In summary, a number of questions related to the long-term evolution of the Earth system under zero emissions at different GWLs can be addressed using the TIPMIP ESM simulations. These include:

- What long-term change is the world committed to under zero-emissions at different GWLs, and what feedbacks occur in models sampling these conditions?

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- What are the long-term and committed regional changes at different GWLs? Do regional climate change patterns depend on GWL?

- Will incremental climate changes in the different zero emission runs lead to key thresholds being exceeded? Will these result in major impacts on ecosystems and/or society?

- How different are the climate responses between different GWLs and what impacts are avoided by staying at a lower GWL?

- How different is the climate response at the same GWL as a function of the path followed to reach it? For example, contrasting zero-emission runs at GWL = 2 ˚C branched directly from the positive CO_2-emission ramp up, versus a zero-emission run also at GWL = 2 ˚C, branched from a negative CO_2-emission ramp-down itself started from a GWL = 4 ˚C zero-emission run (i.e. after a warming overshoot).

- If abrupt changes are triggered, in either the positive or zero-emission runs at a given GWL, are these changes reversible when global temperatures are cooled and zero-emission (warming stabilization) is realized at a colder GWL?

To answer these questions, including a robust estimate of the associated uncertainty, an ensemble of simulations is required, initially spanning multiple models, and subsequently also sampling internal variability per model (i.e. initial condition ensembles). Single model simulations can differ significantly from each other, examples include historical Arctic Sea ice (Notz et al., 2020) and AMOC representation (Weijer et al., 2020) in CMIP6 models, and their subsequent evolution in future projections (e.g. Romanou et al., 2023). Regional climate change patterns are even more challenging as they strongly depend on the driving large-scale circulation patterns (Kjellström et al., 2018), with internal variability playing an even larger role at regional scales (Koenigk et al., 2020). Internal variability can be partially addressed by running long zero-emission simulations. However, as the mean state keeps evolving during the stabilisation period, late and early periods in these simulations may be different in both mean state and internal variability. In addition to internal variability, different ESMs can lead to very different regional and cascading changes across Earth system components at the same GWL (Evin et al., 2024). Dealing with these model-to-model differences calls for an ensemble of models running the same set of experiments. The Tier 1 protocol requests 300-year zero-emission simulations (where possible 500-year). This may not be sufficiently long to fully answer questions pertaining to the new equilibrated state of regional and global climate at different GWLs. It is thus important to link this work with activities looking at timescales exceeding a few hundred years, as done in King et al. (2024) and Rugenstein et al. (2020).

4.3 Reversibility

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Although there is no unique definition for the degree of reversibility of Earth system changes, the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (IPCC, 2022) defines it as the ability of the Earth system to reverse anthropogenic-induced changes and return to a state equivalent to the initial state prior to the introduction of the external perturbation (e.g. a preindustrial condition), on a certain timescale. Irreversibility, in contrast, implies a suite of physical and/or biogeochemical forcings and system responses that moves a system across some critical threshold, from one stable equilibrium to another (Lenton et al., 2008), with the original state unattainable under reasonable bounds of modified forcing or time periods. The concept of irreversibility or hysteresis is, therefore, closely related to that of tipping points (van Nes et al., 2016; Armstrong McKay et al., 2022; Lenton et al., 2023).

Current literature suggests irreversible Earth system change may result either from highly nonlinear system responses to an external forcing, or state-dependent responses to this forcing, or a combination of both (Litzow et al., 2016; Scheffer et al., 2015; Santana-Falcon et al., 2023; Heinze et al., 2023; Ritchie et al., 2023; Fröb et al., 2024). The question whether Earth system changes are reversible is therefore connected to the response of key Earth system processes to variable external forcing (Frölicher et al., 2010; Kug et al., 2022), where this forcing might be external to the Earth system itself (e.g. anthropogenic CO_2 emissions or solar variability) or internal to the Earth system but external to a specific Earth system phenomenon (e.g. changed ENSO variability and its impact on Amazon resilience). Details of the external forcing matter, for example, changes in either the magnitude or duration of forcing, such as the rate of warming or the magnitude and duration of warming overshoot, are thought to be important factors in driving a system towards irreversible change (Schwinger et al., 2018; Jeltsch-Thömmes et al., 2020; Ritchie et al., 2023, 2024). Timescales are of particular importance for the interior ocean and ice sheets where response times are long (Bertini and Tjiputra, 2022).

The TIPMIP Tier 1 experiments allow us to address a number of questions associated with the potential reversibility of Earth system change. A first question concerns how reversible Earth system changes and related climate impact drivers, identified at different warming levels (i.e. in the zero emission runs), are. While previous assessments (e.g. IPCC Special Report on Global Warming of 1.5°C (IPCC, 2022), IPCC 6th Assessment Report WGI (IPCC, 2023)) provide some insight into how far such changes differ between warming levels, the question of how reversible the identified changes are, remains uncertain. Closely related to the zero emission commitment (ZEC), are important open questions related to the quantification of feedbacks at different warming levels, as well as the state-dependence of processes involved in irreversible change (e.g. the future state, and response at that state, of ice sheets, permafrost, forest ecosystems, etc.). King et al. (2020) suggest this question needs to also consider the duration the Earth system is at a certain warming level and whether the forcing (i.e. emissions) causing this state change is transient or stabilized.

Another important question relates to the degree of connectivity between global and regional Earth system change, and how changes in one location (or component) of the Earth system can cause changes elsewhere. Emerging literature (Armstrong

McKay et al., 2022; Lenton et al., 2023; Wunderling et al., 2024) suggest there are hotspots or tipping elements that, once triggered, may influence the stability of other parts of the Earth system. The suggestion is that an initial global-scale change can induce a major regional (abrupt) change that itself amplifies the global-scale signal or triggers independent regional abrupt changes elsewhere, through a cascade of interactions and feedbacks (Wunderling et al., 2022). Quantifying these risks requires an improved understanding of the linkages between global change and regional responses, including the mechanisms underpinning such region-to-region interactions. Recent studies highlight how anthropogenic forcing has the potential to significantly alter prominent modes of climate variability, such as the Inter-Tropical Convergence Zone (Kug et al., 2022) or the El Nino Southern Oscillation (ENSO, Vaittinada Ayar et al., 2022; King et al., 2024; Cassidy et al., 2024), with the potential for these changes to induce further, potentially amplifying regional responses in specific Earth system domains.

A third key question concerns long-term committed change at different stabilized warming levels, such as accumulated Greenland or Antarctic ice loss, or permafrost thaw, and its potential reversibility when global warming is subsequently reduced. Recent work (Schleussner et al., 2024) suggests reducing global temperatures can limit long-term climate risks compared with merely stabilizing warming (i.e. negative emissions compared to net-zero emissions), including for sea-level rise and cryosphere changes. However, there are deep uncertainties in the long-term response of the Earth system associated with the severity and duration of warming before cooling is realized, as well as how accurately models represent the long-term (multi-century) response across the Earth system. Recent advances in the degree of process-realism and process-interaction in Earth system models participating in TIPMIP will help address this question. For example, ESMs are now beginning to include fully interactive treatment of phenomena such as continental ice sheets, permafrost, wildfires, and are also increasingly running in emission mode for GHGs, allowing a more complete representation of interactions between climate change, the carbon cycle, and the primary driver of warming, atmospheric CO_2 (Sanderson et al., 2024).

4.4 Earth system responses to negative emissions

The magnitude of global warming scales approximately linearly with cumulative CO_2 emissions (IPCC 6th Assessment Report Summary for Policymakers; IPCC, 2023). This implies global mean temperatures should approximately stabilize at net-zero CO_2 emissions, and that reducing CO_2-induced warming will require net-negative global CO_2 emissions. Section 4.3 discussed reversibility of aspects of the Earth system. The TIPMIP ESM simulations will also allow us to more fully explore the efficacy and implications of reversing global temperature through negative CO_2 emissions, as well as investigate the mechanisms controlling the Earth system response to these negative emissions.

The linearity of warming arises from consideration of the climate response to forcing – both the transient response and the rate of adjustment to constant forcing – as well as the radiative forcing that arises from CO_2 emissions (Allen et al., 2022), the latter being controlled by the airborne fraction of emitted CO_2. The resulting relationship – known as the transient climate response

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to cumulative carbon emissions (TCRE) – gives a monotonic and, importantly, approximately path-independent peak-warming response to CO_2 emissions. While some studies have shown that this relationship may break down for both very large cumulative emissions and strong negative emissions (e.g. Zickfeld et al., 2015; Zickfeld et al., 2021), these results are based on single model studies. It remains unclear how reversible the TCRE relationship is, but to first order we expect global temperatures to reverse by approximately the same amount if CO_2 is removed in the same manner as it was added under positive emissions and warming, particularly from lower warming levels. Koven et al. (2022) showed that deviations from reversibility of TCRE across multiple models are related to the legacy response to previous emissions and correlate with the zero emissions commitment for each model – models with a positive ZEC show an overshoot of temperature under negative emissions while models with a negative ZEC may undershoot – i.e. they may reverse more quickly than the negative emissions alone would imply. Models with a ZEC close to zero are much closer to reversible along the same TCRE gradient. Models with a higher ZEC, and importantly if ZEC becomes increasingly positive at higher warming levels, may exhibit reduced sensitivity to negative emissions –i.e. they may cool slower than they warmed in the ramp-up phase. Extending the CMIP7 Fasttrack flat10 experiments (Sanderson et al., 2024), TIPMIP samples multiple GWLs, allowing a systematic analysis of multi-model and multi-GWL responses to positive, zero, and globally net-negative, emissions, supporting an analysis of the thermal, carbon, and feedback controls on the total Earth system response (Williams et al., 2025).

Carbon sink dynamics under negative emissions are qualitatively understood, although models differ in the quantitative magnitude of this response. Over the last century or so, CO_2 emissions have caused a rapid rise in atmospheric CO_2 concentration and natural carbon sinks – both land and ocean – while removing some of this have not kept up and so act to increase their sink rates in step with the emissions (Raupach et al., 2014). When CO_2 emissions stop increasing, atmospheric CO_2 declines and natural sinks weaken, eventually saturating, in particular the land biosphere (Silvy et al., 2024). Under negative CO_2 emissions, atmospheric CO_2 concentration strongly declines, and the natural sinks eventually reverse as both ocean and land ecosystems outgas excess carbon dioxide (Jones et al., 2016; Koven et al., 2022). Thus, in the long term, the same processes which lead to natural sinks opposing positive emissions also lead to the natural carbon cycle opposing CO_2 removal, i.e. for every ton of CO_2 removed by anthropogenic activity, atmospheric CO_2 concentrations will decline by less than one ton.

TCRE is the product of the transient climate response and the airborne fraction of CO_2 (Gillett et al., 2013; Williams et al., 2020). Process uncertainty in determining the magnitude of TCRE is split approximately equally between physical feedbacks and carbon cycle feedbacks (Jones and Friedlingstein, 2020) although this balance has evolved over CMIP generations as model complexity has developed. Uncertainty in the carbon cycle response to negative emissions is likely dominated by land ecosystems in the same way as it is for the response to rising emissions (Jones and Friedlingstein 2020), although on longer timescales the land sink will saturate more quickly leaving a larger role for the ocean carbon uptake to dominate (Randerson

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et al., 2015). The TIPMIP ESM experiments will allow an improved quantification of the various contributions to uncertainty in the carbon cycle response to negative emissions based on the very latest generation of ESMs.

Cassidy et al. (2024) and Chamberlain et al. (2024) show strong regional changes in climate following net zero emissions even when global mean temperatures are approximately stable. Continued warming in the Southern Ocean, while land temperatures cool, may be due to a delayed upwelling of heat, which similarly delays the onset of warming in the Southern Ocean during positive emissions (Armour et al., 2016). Continued Southern Ocean warming, particularly at depth, is also associated with a slowing of the overturning circulation at high subpolar latitudes, decreasing the export of cold Antarctic Bottom Waters into the global ocean (Chamberlain et al., 2024). This delayed heat release has the potential for globally significant effects if it changes regional cloud feedback (Andrews et al., 2022; Gjermundsen et al., 2021). The amount and rate of heat released from the Southern Ocean may also have a large effect on the dependence of the system to the (surface) warming level achieved before zero and negative emissions are realized (i.e. different amounts of sequestered heat in the sub-surface ocean available to influence surface temperatures at some later date). MacDougall et al. (2020) found in a limited number of ZECMIP models that higher levels of emissions may lead to greater ZEC values and hence, by extension, an expectation of different reversibility from higher warming levels, but this has never been studied in a multi-model context. Analysis of TIPMIP results will elucidate the multi-model response and shed light on the dependency of this response to global warming level.

5 Initial results

In this section we present a small set of examples of the experiment protocol in action, as realized by a number of contributing ESMs. A more thorough analysis of the full experiment protocol is intended once the majority of models making these runs have completed them and converted their data. These studies will be reported on in subsequent papers.

In Fig. 2, for one example model only (GFDL_ESM2M, Dunne et al., 2013), we show the full pathway of simulations, plotting global mean atmospheric CO_2 mixing ratio (referred to as atm.CO_2 hereafter) and global mean surface air temperature (GMSAT hereafter). The positive emission (ramp-up) run branches from an esm_piControl that is temporally stable with respect to both atm.CO_2 and GMSAT, with atm.CO_2 rising throughout the ramp-up to a value of ~850 ppm by the time GWL = 4 °C is reached. GMSAT closely follows a warming rate of 2 °C per century through the ramp-up in this model. At GWL = 2 °C the zero-emission run sees a slow reduction in atm.CO_2 as (primarily) the ocean and land sinks continue to take up excess CO_2 from the atmosphere. This decrease in atmospheric CO_2 will lead to a small negative trend in radiative forcing, which on its own would be expected to lead to a decrease in GMSAT in the zero-emission run (Williams et al., 2025). This is not the case, with a ZEC value slightly above zero being realized in this model at GWL = 2 °C. This slight positive ZEC indicates there is a committed warming at the branch point from the positive emission run into the zero-emission run, represented by heat taken up during the ramp-up and residing in the subsurface ocean (Williams et al., 2025). During the zero-emission run this

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sequestered heat has time to reach the surface of the ocean, overcompensating the cooling tendency from the decrease in CO_2 radiative forcing, with the combined result being a small warming of the surface (i.e. a positive ZEC). In the zero-emission run started at GWL = 4 °C there is a clear tendency for this model to have a more positive ZEC than at 2 °C, suggesting the impact of committed (deep ocean) warming on surface temperatures in the 4 °C zero-emission run more strongly outweighs the cooling due to the negative trend in atmospheric CO_2. The model also shows varying timescales in ZEC, with near-zero ZEC during the first hundred years of the 2 °C zero emissions simulations, followed by a period of more continuous warming (Frölicher and Paynter, 2015). The two negative emission runs, started 50 years into the zero-emission runs at 2 °C and 4 °C, suggest a near symmetrical global cooling compared to warming in the ramp-up, although the degree of this symmetry needs to be assessed in more detail. The zero-emission run, branched at GWL = 2 °C off the ramp-down started from 4 °C, also suggests a modestly positive ZEC. It is noteworthy that atm.CO2 at the point GWL reaches 2 °C in the ramp-down is significantly lower than atm.CO_2 at GWL = 2 °C in the ramp-up, suggesting that to return to a GWL value of 2 °C after overshoot to 4 °C requires atmospheric CO_2 to be significantly lower than for the same value of GMSAT before the overshoot (Held et al., 2010).

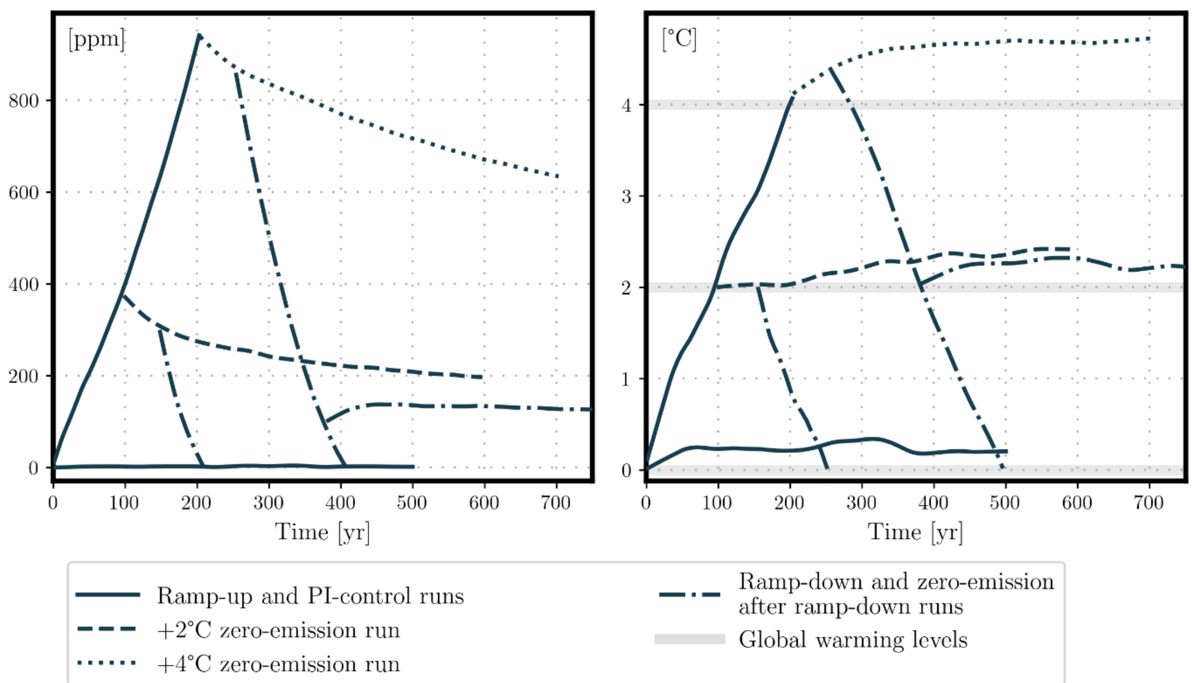

Figure 2. An example of the TIPMIP ESM protocol based on a single model (GFDL_ESM2M, Dunne et al., 2013) simulations. The left panel shows global mean atmospheric CO_2 concentration (atm.CO2). The right panel shows global mean surface air temperature (GMSAT).

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Figure 3 shows the same as Fig. 2, except only for the positive emission (ramp-up) and zero-emission runs at 2 °C and 4 °C, this time for nine models that have so far made the TIPMIP runs. Note at that time of writing, not all models have completed the zero emission runs, some models have run 500 years of zero-emission while others have only run 300 years. We plot the full length of run from each model simulation. When plotting the multi-model results, it is clear that different CO_2 emission rates (and therefore different atmospheric CO_2 concentrations) are required to realize a near common 2 °C per century warming across models. Models closely follow the 2 °C per century warming from 0 °C (i.e. piControl) to 2 °C. Above GWL = 2 °C there is more spread in warming rates, suggesting TCRE is not completely linear across all GWLs (and emitted CO_2) in all models. The combination of common warming rates driven by different atmospheric CO_2 increases means there is significant spread across models in atm.CO_2 at both GWL = 2 °C and 4 °C, with this difference growing from 2 °C to 4 °C. The ZEC response (trend in GMSAT) at 2 °C varies across models. A few models show a weakly negative ZEC and a few a weakly positive ZEC. Two models essentially have ZEC = 0.0. The ensemble mean ZEC at 2 °C is very close to zero. This spread in the ZEC response increases at GWL = 4 °C, with an increased tendency for positive ZEC in a number of models, with a few models suggesting the ZEC response becomes more positive with time through this zero-emission run.

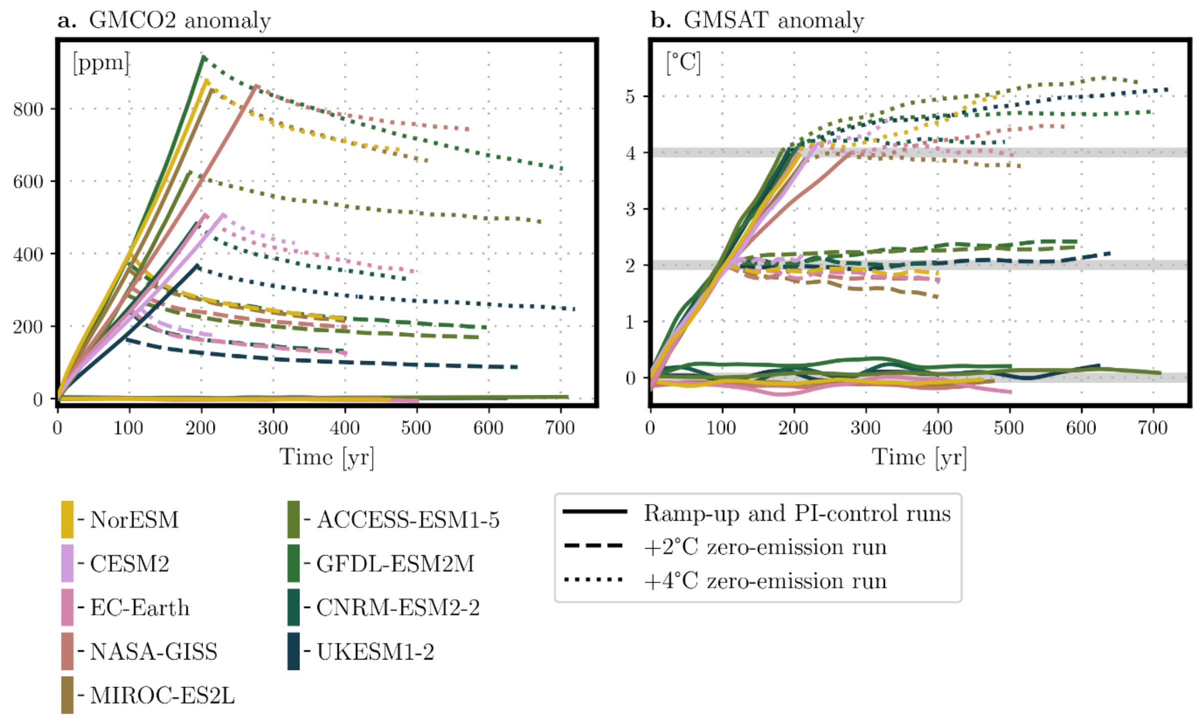

Figure 3: Global mean atmospheric CO_2 (atm.CO_2 in ppm, left panel) and GMSAT (°C, right panel) for the piControl (full line), ramp-up (full line) and zero emission runs at GWL = 2 °C (dashed lines) and 4 °C (dotted lines), as simulated by nine ESMs (listed in the figure legend).

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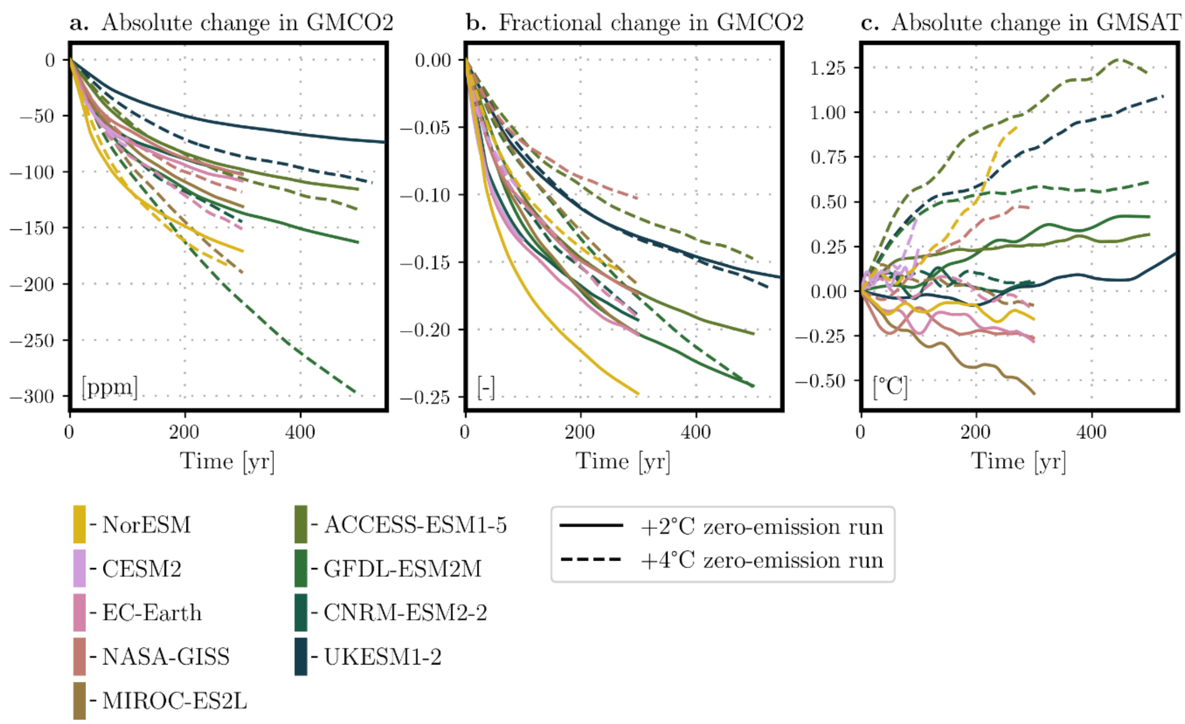
In Fig. 4 we plot the change in model's atm.CO_2 and GMSAT in the zero-emission run normalized to zero at the start value of each zero-emission run. For atm.CO_2 we plot both the absolute change (in ppm) and the fractional change relative to the start value. Absolute atm.CO2 decreases slightly more rapidly in the GWL = 4 °C zero-emission run than in the one started at GWL = 2 °C. When plotted as a fractional change there is less difference in the atm.CO_2 trend between these two GWLs. The absolute change in GMSAT, relative to the value at the start of the zero-emission run, is generally more positive at GWL = 4 °C than at GWL = 2 °C (i.e. only one model shows a very slight negative ZEC at GWL = 4 °C while five models clearly show a significant positive ZEC at this GWL that is more positive than the value at GWL = 2 °C).



780

Figure 4: Change in global mean atmospheric CO_2 concentration and GMSAT for the two zero emission runs expressed as anomalies relative to each value at the start of the respective zero emission run. Left panel: absolute change in atm.CO_2 in ppm, middle panel: fractional change in atm. CO_2, and right panel: change in GMSAT in °C.

As more models complete the TIPMIP ESM protocol we plan to intercompare the multi-model ensemble with an emphasis on the four broad topics introduced above in Sects. 4.1 to 4.4.

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6 Summary and conclusions

We have introduced a new ESM experiment protocol, developed as part of the TIPMIP project (Winkelmann et al., 2025). The protocol assumes ESMs are run in CO_2-emission mode (i.e. full carbon cycle with atmospheric CO_2 a prognostic model variable). The protocol requires a constant emission of CO_2, derived from each model's TCRE, to give a global mean warming rate of 2 °C per century. At specified levels of warming (2 °C and 4 °C) relative to each model's pre-industrial global mean surface air temperature (GMSAT), CO_2-emissions are set to zero and runs branched into (so-called) zero-emission (climate stabilization) experiments. These zero-emission runs continue for 300 years (500 years if possible). 50 years into each zero-emission run, CO_2-emissions are set to the negative of the positive emission rate used in the warming ramp-up run. These two negative CO_2 emission runs (started from GWL = 2 °C and 4 °C) are continued until GMSAT cools below the original pre-industrial GMSAT. When the negative emission run started from GWL = 4 °C first drops below GWL = 2 °C a zero-emission run is branched off this, completing the Tier 1 set of experiments.

The resulting ESM experiments will be used to assess (i) the risks, consequences, and drivers of abrupt/rapid Earth system change (tipping points) at different levels of global warming, (ii) the long-term response of the Earth system to zero CO_2-emissions, (iii) the behaviour of the Earth system under prescribed negative CO_2-emissions following a specified (magnitude and duration) of global warming overshoot, (iv) the efficacy of negative CO_2 emissions in driving global cooling, and (v) the reversibility of Earth system change under a pathway of positive (warming), zero (stabilization), and negative (cooling) CO_2 emissions. The primary advantage of the protocol is that we can control the rate of global warming and cooling across models using a TCRE-based CO_2 emission rate specific to each model. This enables a multi-model intercomparison of the above topics in a common global warming/cooling space.

The protocol is being actively run by 13 ESMs, with a common set of diagnostics being archived to the Earth System Grid Federation (ESGF), initially following the CMIP6plus protocol. This paper is to facilitate the TIPMIP ESM protocol becoming a CMIP7 community MIP. We envisage further developing the Tier 1 experiment protocol in the coming years as part of CMIP7.

Code and Data availability

The plotting code and the underpinning data behind Figures 2, 3 and 4 is available at https://zenodo.org/17055322 (Bossert, 2025). ASCII files are presented for each model for global mean surface air temperature (GMSAT) and global mean atmospheric CO2 (atm.CO2). No other original datasets were used in this article.
The diagnostic request for the TIPMIP ESM phase 1 experiments is available at https://doi.org/10.5281/zenodo.15189530.

https://doi.org/10.5194/egusphere-2025-3604
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Author contribution

CJ wrote the paper, with text contributions from DD, CDJ, TK, SL, BS, RS, KW and SY. IB analysed the TIPMIP ESM results and made Figs. 2,3 and 4. HJ made Fig. 1 and prepared the manuscript for submission to GMD. All authors (i) contributed to the development of the TIPMIP ESM experiment protocol and (ii) commented on, and contributed, to the developing paper. A number of co-authors ran the ESM experiments outlined in the paper and submitted results that led to Figs. 2, 3 and 4.

Competing interests

One author is a member of the editorial board of GMD.

Acknowledgements

Financial Support

This research has been supported by TerraFIRMA "Future Impacts, Risks and Mitigation Actions in a changing Earth system" is funded by the UKRI Natural Environment Research Council (grant reference NE/W004895/1); European Union Horizon 2020 project ESM2025 (grant agreement no. 101003536); Horizon Europe project OptimESM "Optimal High Resolution Earth System Models for Exploring Future Climate Changes" (grant agreement no. 101081193); the UK government's Horizon Europe funding guarantee (grant numbers, 10103098, 10043072); TipESM "Exploring Tipping Points and Their Impacts Using Earth System Models" funded by the European Union (grant agreement no. 101137673. DOI: 10.3030/101137673, TipESM contribution no. XX); ClimTip "Quantifying climate tipping points and their impacts" funded by the European Union's Horizon Europe programme. (grant agreement no. 101137601, ClimTip contribution #78); OCEAN ICE "Ocean Cryosphere Exchanges in ANtarctica: Impacts on Climate and the Earth system" funded by the European Union (grant agreement no. 101060452, **10.3030/101060452**); OceanICU "Understanding Ocean Carbon" funded by European Union Horizon Europe (grant agreement no. 101083922); European Research Council Q-ARCTIC (grant agreement no. 951288); the Met Office Hadley Centre Climate Programme funded by DSIT; Research Council of Norway under grant agreements, TRIFECTA (334811) and NAVIGATE (352142); the Program for the Advanced Studies of Climate Change Projection (SENTAN; grant no. JPMXD0722681344) from the Ministry of Education, Culture, Sports, Science and Technology, Japan; the Australian Government under the National Environmental Science Program (NESP); the German Federal Ministry of Education and Research project MOMENT (BMBF 03F0931F); the US National Science Foundation (NSF) National Center for Atmospheric Research (NCAR) under Cooperative Agreement no. 1852977; Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modeling Program of the U.S. Department of Energy's Office of Biological &

https://doi.org/10.5194/egusphere-2025-3604
Preprint. Discussion started: 23 September 2025

Environmental Research (BER) via National Science Foundation (NSF) IA 1947282 (DE-SC0022070); NASA-Modelling Analysis and Prediction, ModelE development and N3-MAP23-0018, NNH23ZDA001N-MAP.

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