

The TIPMIP Earth system model experiment protocol: phase 1

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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 CO₂-emission mode, with atmospheric CO₂ a predicted variable. Forcing for the protocol consists solely of a constant emission of CO₂, based on each model's transient climate response to cumulative emissions of carbon dioxide (TCRE) value, to give a common global mean surface warming rate of 2 °C per century. This positive emission (ramp-up) 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), CO₂ 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, CO₂ 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 the 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 under net zero CO₂ emissions at a range of global warming, the long-term Earth system response to net zero CO₂ emissions, the response to net negative CO₂ 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) CO₂ 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 (CO₂) 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 CO₂ 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

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~~common-net~~ negative CO₂ emission pathways (CO₂ removed from the atmosphere) after a common time period under zero emissions.

80 There is increasing interest in global warming overshoot scenarios (i.e. temporary exceedance of a global warming target that is returned to at some later date; (Schleussner et al., 2024; Reisinger et al., 2025)) and in the long-term response of the Earth system to net zero CO₂ emissions at temperatures warmer than today (Allen et al., 2022; Frankhauser et al., 2022). Key outstanding questions include, ~~the likelihood, timing, and magnitude of overshoot~~, the consequences arising from such an overshoot, the feasibility of cooling the planet back from a peak warming to a (stabilized) target level, the ~~risk~~ of hysteresis once a stabilized climate is achieved, and the long-term response of the Earth system to net-zero emissions at temperatures warmer than today.

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Our protocol lends itself to addressing a number of ~~these questions, 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 CO₂ emissions~~. Areas of particular ~~interest focus~~ include (i) the risks and consequences of triggering Earth system tipping points (Winkelmann et al., 2025), (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 CO₂ emission pathway, and (iiiiv) the overall efficacy of negative~~
90 CO₂ emissions in driving global cooling, including ~~the regional patterns of this cooling, and (iv) the reversibility of any induced changes following a negative CO₂ emission pathway~~.

The protocol ~~described in this paper~~ assumes ESMs are run in CO₂-emission mode, meaning atmospheric CO₂ 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 CO₂ emissions. An effort to develop an analogous experiment protocol for models run in (prescribed) CO₂-concentration mode is underway and will be reported in a subsequent paper. ~~Thiese~~ 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 ~~se coupled~~ ESM experiments.

105 TIPMIP ESM experiments began as part of CMIP6plus (an extension to CMIP6 after the formal project had closed). This paper describes the experiment protocol in detail as preparation for participation in CMIP7 (Dunne et al., 2025). 38 MIPs have so far registered to take part in CMIP7, with the full list available at WCRP: <https://wcrp-cmip.org/mips/#registered-mips>, last access 9 February 2026. TIPMIP ~~has some commonality, and potential for collaboration~~ with a number of CMIP7 MIPs, including C4MIP, CDRMIP, AERA-MIP (Silvy et al., 2024), as well as ScenarioMIP (van Vuuren et al., 2025) and the

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[flat10MIP experiments \(Sanderson et al., 2024\) that are part of the CMIP7 Assessment Fast Track \(Dunne et al., 2025\). We discuss areas of potential collaboration with these MIPs in section 3.4.](#)

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, CO₂ 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).

The TIPMIP ESM Tier I 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~~ ~~Studies also~~ 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 (Myksovoll 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 ~~studies 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 ~~of 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, e~~Considerable uncertainties remain around ~~the~~ 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). 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. Figure 1 presents a schematic of the protocol and Bbox 1 summarizes the key assumptions underpinning the protocol. All experiments are to be run in CO₂-emission mode (i.e. full simulated carbon cycle with prognostic atmospheric CO₂). 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 CO₂ -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 (defined as year A). The ramp-up run is forced by a positive global mean CO₂ 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; Matthews et al., 2009)) to give a global mean surface air temperature (GMSAT) warming rate of 2 °C per century. The best way to calculate TCRE is using the new flat10 experiment protocol (constant CO₂ emission of 10 PgC yr⁻¹), as documented in Sanderson et al., (2024)). If only a transient 1% CO₂ run (1pctCO₂) is available then we recommend the method of Arora et al. (2020, their equation 21, reproduced below) for calculating TCRE. We suggest using the method of Arora et al. (2020) to calculate model TCRE value, specifically equation 21 and the averaging timescales suggested therein.

$$TCRE = \frac{\Delta T_{2\times CO_2}}{\Delta \bar{E}_{CO_2}} \quad (1)$$

Where $\Delta T_{2\times CO_2}$ is the Transient Climate Response (TCR), defined (for a given model) as the change in GMSAT relative to its pre-industrial value at the time atmospheric CO₂ concentrations in a 1pctCO₂ run (Eyring et al., 2016) have doubled, occurring after 70 years. $\bar{E}_{2\times CO_2}$ is the cumulative carbon emissions at the time of CO₂ doubling in the same experiment. TCRE is expressed in units of °C per exagram (1000 Pg) of carbon. 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 CO₂ emissions, we suggest emitting with a spatial-pattern that mirrors that used for the CMIP6 historical CO₂ emissions (for example the pattern of emissions for the final year of the CMIP6 historical period (2014)), scaled to give the required TCRE-based emission rate needed, though given the long lifetime of well-mixed atmospheric CO₂, the spatial pattern of emissions is likely of secondary importance.

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Apart from the introduction of positive CO₂ emissions, everything else in the ramp-up is unchanged from the esm_piControl
210 ~~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), CO₂
215 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 ~~the year~~
~~A~~ in the esm_piControl from which the ramp-up started. The ZE run start date is ~~defined as set to~~ January 1st of the year
directly after the first year GWL = 2 °C is diagnosed. The ZE simulation is run with CO₂ emissions set to zero for a minimum
220 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 CO₂
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 ~~the 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*
225 *-> 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 ~~this year~~ 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 ~~this~~ ZE run ~~at GWL = 4 °C~~ a X GtC yr⁻¹ negative emission ramp-
230 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. Box 1 summarizes the main
assumptions underpinning the experiment protocol and Table 1 ~~summarises~~ the various simulation steps in the TIPMIP Tier
235 1-ESM protocol.

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<u>Simulation name</u>	<u>G</u> <u>Warming Level</u> <u>WL</u> -start value	CO ₂ emission GtC yr ⁻¹	Run length	<u>Warming</u> <u>Level</u> <u>GWL</u> 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

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 CO₂ 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 CO₂ emissions) in the ramp-up. Put another way, we expect a unit emission of CO₂ (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 CO₂ emissions and induced warming are relatively small) or later in the same run (when accumulated CO₂ emissions are larger and induced warming is also larger). This assumption of linearity appears **very**-accurate at lower warming levels (modest accumulated CO₂ emissions) but becomes less accurate at higher warming levels (greater accumulated CO₂ 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 CO₂-emission rates linked to each model's TCRE~~), we chose 2 °C per century as this is the approximate rate of observed ~~warming 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 ~~Z~~zero-~~E~~missions ~~C~~commitment (~~ZEC~~, 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 CO₂ 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 simulation 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 warming due to ~~anthropogenic~~ greenhouse gas (GHG) emissions (Gillet et al., 2021; Smith and Forster, 2021). ~~Anthropogenic a~~aerosol emissions also vary significantly across different future emission scenarios, ~~such as 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~~ ~~result~~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 ~~and~~. ~~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 ~~historical run~~, 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~~
300 ~~ESM protocol so feedbacks between land-use change, regional climate, and forest response can be captured (Wu et al., 2021; Cano et al., 2022).~~

~~The Our~~ protocol ~~also~~ does not consider non-CO₂ anthropogenic GHG emissions, such as methane (CH₄), ozone (O₃), nitrous oxide (N₂O) or chlorofluorocarbons (CFCs and HCFCs). While these are important forcers, for example when combined giving
305 an historical radiative forcing ~75 % of that due to anthropogenic CO₂ emissions (Chapter 7, ~~IPCC: Climate Change 2021 WGI, 2023a~~), 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 CO₂ emission. Omission of anthropogenic CFCs and HCFCs also means there will be no stratospheric ozone depletion (Solomon, 2019) in our experiments.

310 Because our protocol is forced solely by CO₂ 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 CO₂ than equivalent multi-gas and land-use scenarios at the same GWL. This is primarily because the positive radiative forcing arising from non-CO₂ WGHGs (e.g. methane, ozone, nitrous oxide etc) in the multi-gas scenarios is being achieved (in a warming sense) by
315 CO₂ 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
320 models ~~sliding groups able to contribute~~ing. 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 112 ESMs already ~~expressing an interest to running~~ these experiments. Nevertheless, we recognize the need for more ensemble members. For instance, a bifurcation in
325 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)

330 ~~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
335 running if resources allow. These include:

1. Extend the ~~three two~~ zero-emission 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).
- 340 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).
- 345 3. Extend the original esm_piControl so it is sufficiently long to act as a reference for the new zero-emission ZE runs proposed under points 1 and 2.
- 350 4. Increase the ensemble size ~~of all legs of Tier 1, e.g., by starting new ramp-up -> zero-emission -> ramp-down s 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 We~~ suggest a minimum of 30 years separation in the esm_piControl between starting new ramp-up runs.
- 355 5. In addition to zero-emission ZE runs ~~branched off the ramp-up runs~~ at GWL = 2 °C and 4 °C, also perform zero-emission ZE runs off the ramp-up at sampling GWL = 1.5 °C, 3 °C and 5 °C, ~~ideally for a minimum of 500 years each.~~
- 360 6. In addition to the -X GtC yr⁻¹ negative emission runs starting 50 years into each zero-emission ZE run, start identical negative emission runs later into the same zero-emission runs ZE run (after 200 years is recommended).
7. Repeat negative emission runs ~~from the same ZE start points, but rather sampling~~ 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 ~~also propose 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 $X \text{ GtC yr}^{-1}$ to $\text{GWL} = 2^\circ\text{C}$
- One *zero-emission (ZE)* run at $\text{GWL} = 2^\circ\text{C}$ for 200 years
- One *ramp-down* run (started 50 years into the ZE run at $\text{GWL} = 2^\circ\text{C}$), run back to $\text{GWL} < \text{pre-industrial}$.

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 ~~before zero-emission runs are branched at common GWLs. The~~ zero ~~and negative emission runs are not guaranteed to exhibit common temperature evolution across each model, rather these are emergent properties of each model. runs started at the same GWLs after the same amount of warming, and potentially similar cooling rates in the negative emission runs. The protocol acceptsing~~ 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 ~~are similarities between is some commonality in the two sets of experiments, the TIPMIP and flat10MIP experiments, there are sufficient differences and complementarity to make joint analysis of model responses in common-GMSAT versus common- CO_2 emisisonemission space will help understand differences seen between the two protocols when run by the same model. collaboration across the MIPs productive.~~ The flat10 set of experiments (ramp-up, zero-emission, and ramp-down) are 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 $+10 \text{ GtC yr}^{-1}$ for all models) ~~and then used to inform the positive emission rate in TIPMIP. 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 ~~at which net zero CO_2 emission runs start.~~ The state-dependence of ZEC and ~~the~~ response to negative emissions is a particularly useful and unique analysis ~~opportunity~~ offered by the TIPMIP ~~simulations~~

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Earth system change and regional patterns of change seen in the TIPMIP experiments can also be compared with results from
395 ScenarioMIP (O'Neill et al., 2016; van Vuuren et al., 2025) and CMIP7 DECK (diagnostic, evaluation and characterization of
klima) experiments (e.g. 1pctCO₂ and abrupt 4xCO₂ runs, Dunne et al., 2025) at similar transient global warming levels. This
will provide information on the impact of staying long-term at, ~~or close to,~~ a given GWL (~~in the TIPMIP zero-emission runs~~)
compared to transiently passing through it. Attention will need to be paid to the fact the TIPMIP simulations are forced solely
by variable CO₂-emissions, ~~with other important anthropogenic drivers left at their pre-industrial values.~~ ScenarioMIP forcing
400 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.,
405 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 example, the impact of non-CO₂ radiative forcing
on the spatial patterns of climate change in the AERA-MIP runs stabilized at GWL = 2 °C and the TIPMIP net zero-emission
runs started at GWL = 2 °C. TIPMIP simulations can be compared with AERA-MIP results to explore, for instance, the impact
of non-CO₂ radiative forcing agents on the spatial patterns of climate change under stabilized GMSAT conditions, in particular
410 at GWL = 2 °C, which are sampled both in AERA-MIP and TIPMIP. A difference between the two protocols is the
commonality of model warming rates in the TIPMIP ramp-up runs, as well as the commonality of GWL at which net-zero CO₂
emission runs start. We intend to compare the behaviour of models, particularly tipping point risks and behaviours, in the
TIPMIP runs and those in AERA-MIP where GMSAT is held fixed.~~

415 In CMIP6, ~~t~~The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP, Keller et al., 2018) exploreds the
potential for, and impacts of, CDR deployment. CDRMIP addresses questions concerning reversibility, the response of the
Earth system to atmospheric CO₂ removal (negative CO₂ emissions), and the CDR potential of proposed schemes, such as
afforestation/reforestation and ocean alkalization. The combination of idealized ramp-up (1% CO₂ yr⁻¹) and ramp-down (-
1% CO₂ yr⁻¹) concentration experiments in CMIP6-CDRMIP represent abrupt and non-linear atmospheric CO₂ rates of change,
420 which could compromise the carbon cycle climate feedback estimates (Schwinger et al., 2018; Asaadi et al., 2024). The
emission-driven experimental design in TIPMIP ~~means ensures~~ models follow a smoother trajectory than the ~~artificial~~
discontinuity imposed by a sudden jump from +1 % to -1 % rate of change of atmospheric CO₂. TIPMIP ~~coordinators are in
touch with the and~~ CDRMIP ~~leads developers for CMIP7 to ensure are discussing sharing of simulation data to maximize
utility for both communities 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 ~~may result in means there is a risk~~ only a small number of tipping events occurring in our Tier 1 ensemble. A natural extension to the TIPMIP ESM Tier 1 protocol, in particular using the zero-emission runs at $\text{GWL} = 2^\circ\text{C}$ 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 projects~~.

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

Building Block	Description
$\mu pXpY$	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 $\mu pXpY$. 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. These form the basis of the output filenames convention for TIPMIP under CMIP6plus.

The building blocks are combined to identify the full history of a given experiment, forming part of the output filename for a given model. 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 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.

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

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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 CO₂ emission driven experiments. The experiment names form the basis for identifying different runs under the TIPMIP protocol for a given model.

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 ~~eatastrophie~~, 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, 2023a; 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 Reports 2023 (Lenton et al., 2023, 2025) concludes that some Earth system tipping events are no longer ~~high-impact~~, low-likelihood, ~~high-impact~~ events, rather they are rapidly becoming ~~high-impact~~, high-likelihood, ~~high-impact~~ events.

~~However, large uncertainty still exists with respect to tipping point risks 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 also 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. ESMs 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 to date 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 ~~investigate 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, a~~ 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

capable of simulating gradual permafrost ~~thaw, but~~ 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 CO₂ versus CH₄.~~ Quantifying the impact of ~~missing these~~ processes is essential for advancing our ability to estimate future 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 Offline models representing high northern latitude terrestrial processes will be forced by ESM output to help refine and to refine estimates of annual permafrost thaw dynamics using the methodology of Burke et al. (2020), thereby and 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) and. ~~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 task 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 large 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,~~ supporting enabling a robust quantification of any interactions and possible cascades, ~~based~~

on-state-of-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 CO₂ removal (CDR) and negative CO₂ 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). Furthermore, Cassidy et al. (2024) and Chamberlain et al. (2024) show strong regional changes in climate, particularly over the Southern Ocean, following net-zero emissions even when global mean temperatures are approximately stable. Continued Southern Ocean warming, particularly at depth, is associated with a slowing of the overturning circulation at subpolar latitudes, decreasing the export of cold Antarctic Bottom Waters into the global ocean (Chamberlain et al., 2024). The amount of heat released from the Southern Ocean may also affect the dependence of ZEC on the level of (surface) warming at which zero emissions are realized. 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. This has never been studied in a multi-model context.

It is therefore urgent to understand how the Earth system will respond to different levels of warming stabilization that arise under 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 provides such a data set, 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 or deep-ocean warming and associated thermal expansion, ocean circulation and carbon cycle changes, will continue to evolve long after net-zero emissions are achieved 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., 2021). 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~~ **Slow, gradual warming under net-zero emissions may result in** ~~lead to system~~ thresholds being exceeded, ~~with 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 ~~simulations~~ **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 ~~significant 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 (Soultan et al., 2022; 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 and infrastructure (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 The TIPMIP ESM experiments will be used to drive impact models in ISIMIP (Frieler et al., 2024) to~~ investigate such risks ~~to ecology, biodiversity, and society 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 ~~looking at climate impacts at a given GWL~~ 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 TIPMIP long-term (300+ years) zero-emission simulations in TIPMIP will offer the opportunity to assess valuable insights into what a warmer world will look like if net zero CO₂ emissions are maintained long-term at different GWLs; temperatures are stabilized close to a given GWL for multi-decadal or centennial time periods. In summary, a number of Key questions to address related to the long-term evolution of the Earth system under zero-emissions at different GWLs can be addressed using the TIPMIP ESM include 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?
- What are the long-term and committed regional changes at different GWLs under net-zero emissions? Do regional climate change patterns depend on the 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 achieving net-zero emission at a staying at a lower GWL?
- How different is the climate response to net-zero emissions at the same GWL depending on the as a function of the path followed to reach it (i.e. with or without a temporary warming overshoot)?
For example, contrasting zero-emission runs at GWL = 2 °C branched directly from the positive CO₂-emission ramp up, versus a zero-emission run also at GWL = 2 °C, branched from a negative CO₂-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 robustly, s, 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

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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 and internal variability (Kjellström et al., 2018), with internal variability playing an even larger role at regional scales (Koenig et al., 2020). Internal variability can be partially addressed by the 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 simulate 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 therefore 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

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, 2022a) defines reversibility it as the ability of the Earth system to reverse anthropogenic-induced changes and return to a state equivalent to that 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 the 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 CO₂ 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 I~~ 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~~ ~~are 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, 2022b), IPCC 6th Assessment Report WGI (IPCC, 2023a)) 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~~~~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 ~~some 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 in the Earth system~~. 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 Niño 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 physical climate change and~~ the carbon cycle, ~~and the primary driver of warming, atmospheric CO₂~~ (Sanderson et al., 2024).

4.4 Earth system responses to net negative emissions

The magnitude of global warming scales approximately linearly with cumulative CO₂ emissions (IPCC 6th Assessment Report Summary for Policymakers; IPCC, 2023b). This implies global mean temperatures should approximately stabilize at net-zero CO₂ emissions, and that reducing CO₂-induced warming ~~will require~~ net-negative global CO₂ 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 net negative CO₂ 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 CO₂ emissions (Allen et al., 2022), the latter ~~being~~ controlled by the airborne fraction of emitted CO₂. The resulting relationship – known as the transient climate response to cumulative carbon emissions (TCRE) – gives a monotonic and, ~~importantly,~~ approximately path-independent peak-warming response to CO₂ 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 CO₂ is removed ~~at in the same rate 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 ZEC 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-flat10MIP 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 ~~their~~_{is} response. Over the last century ~~of so~~, CO₂ emissions have caused a rapid rise in atmospheric CO₂ concentration and natural carbon sinks – both land and ocean – while removing some of this₂ have not kept up and so ~~aet to~~ increase their sink rates in step with the emissions (Raupach et al., 2014). When CO₂ emissions stop increasing, atmospheric CO₂ declines and natural sinks weaken, eventually saturating, in particular the land biosphere (Silvy et al., 2024). Under negative CO₂ emissions, atmospheric CO₂ concentration strongly declines, and the natural sinks eventually reverse as both ocean and land ecosystems outgas excess carbon dioxide (Tokarska et al., (2015); 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 CO₂ removal, i.e. for every ton of CO₂ removed ~~(e.g. by CDR)~~_{by anthropogenic activity}, atmospheric CO₂ concentrations will decline by less than one ton.

~~TCRE is the product of the transient climate response and the airborne fraction of CO₂ (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 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 TIPMIP experiment protocol in action, as realized by a number of contributing ESMs. Further a more thorough analysis of the full experiment protocol is intended once the majority of models making these runs have completed the protocol 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 CO₂ mixing ratio (referred to as atm.CO₂ 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.CO₂ and GMSAT, with atm.CO₂ 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.CO₂ as (primarily) the ocean and land sinks continue to take up excess CO₂ from the atmosphere. This decrease in atmospheric CO₂ 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 sequestered heat has time to reach the surface of the ocean, overcompensating the cooling tendency from the decrease in CO₂ 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 CO₂. 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 branched from the zero-emission runs at GWL = 2 °C and 4 °C both have a near symmetrical global cooling compared to warming in the ramp-up, suggesting, for this model, that TCRE is reversible across equivalent positive and negative emission pathways. The degree to which this finding holds for other models will be assessed once the multi-model ensemble is complete. 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.CO₂ 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 CO₂ to be significantly lower than for the same value of GMSAT before the overshoot (Held et al., 2010).

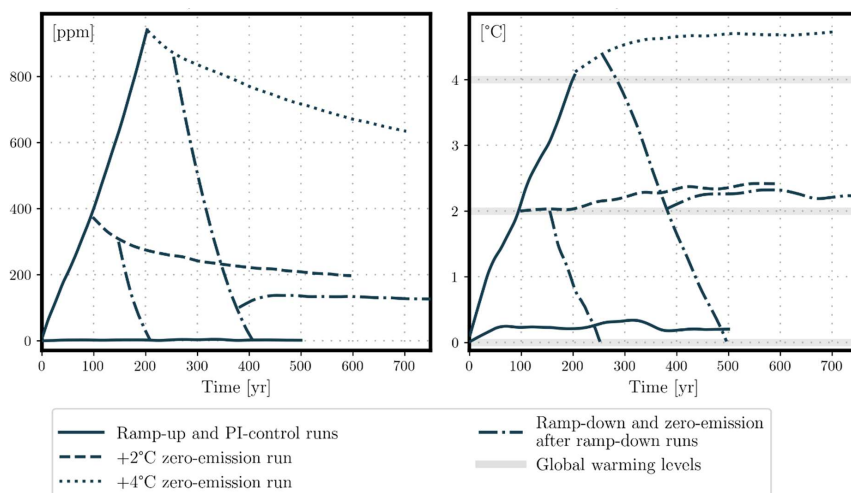
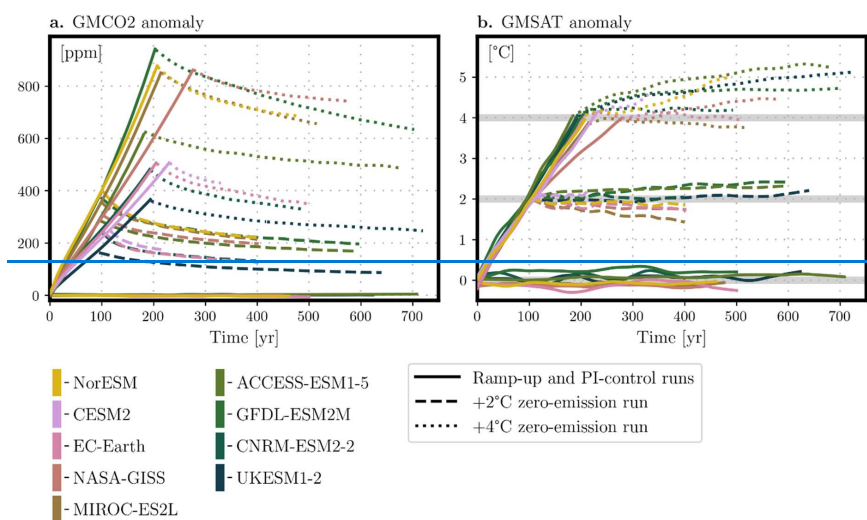


Figure 2. An example of the TIPMIP ESM protocol based on a single model (GFDL_ESM2M, Dunne et al., 2013) simulations. The left panel shows global mean atmospheric CO₂ concentration (atm.CO₂). The right panel shows global mean surface air temperature (GMSAT).

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 these TIPMIP runs. ~~Note at~~ 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~~ Plotting the multi-model results, it is clear ~~that~~ different CO₂ emission rates (and therefore different atmospheric CO₂ 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 CO₂) in all models. The combination of common warming rates driven by different atmospheric CO₂ increases means there is significant spread across models in atm.CO₂ 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, ~~indicating for GWL = 2 °C that achieving net zero CO₂ emissions may allow global warming to stabilize~~. 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.

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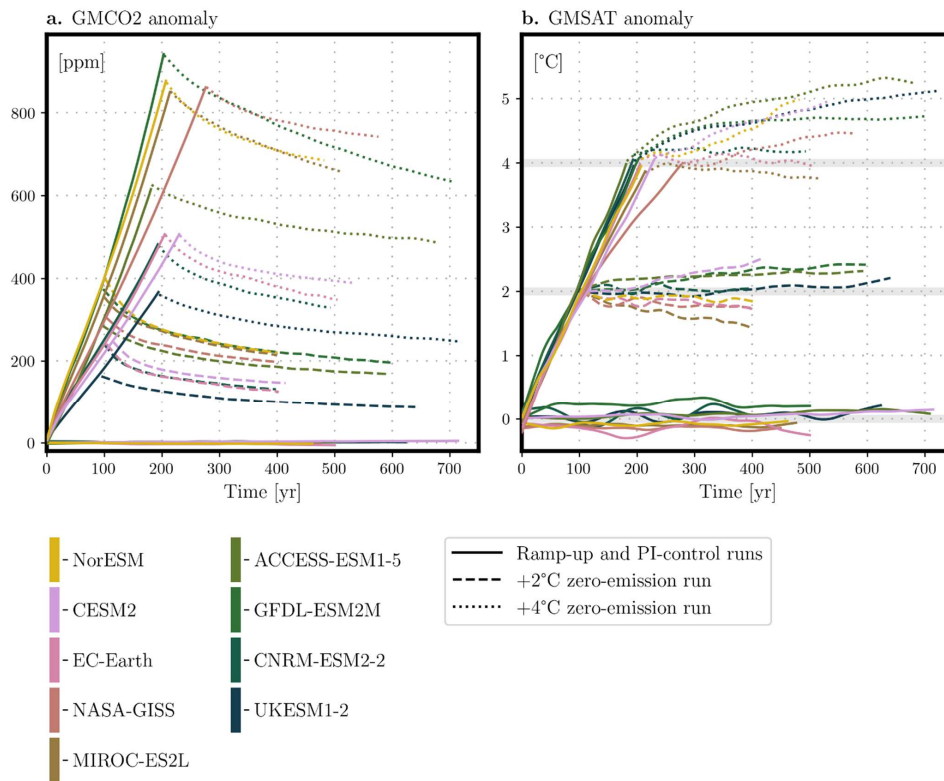


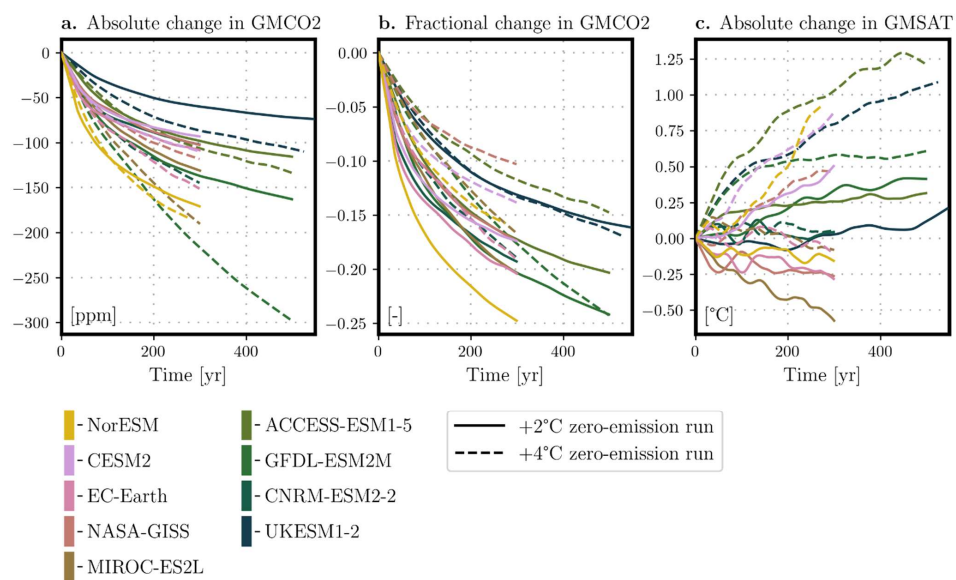
Figure 3: Global mean atmospheric CO₂ (atm.CO₂ in ppm, left panel) and GMSAT (°C, right panel) for the piControl (full line), ramp-up (full line) and zero-emission runs at GWL = 2 °C (dashed lines) and 4 °C (dotted lines), as simulated by nine ESMs (listed in the figure legend).

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In Fig. 4 we plot the change in model's atm.CO₂ and GMSAT in the zero-emission run normalized to zero at the start value of each zero-emission run. For atm.CO₂ 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.CO₂ 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

850

°C than at $\text{GWL} = 2\text{ }^{\circ}\text{C}$ (i.e. only one model shows a very slight negative ZEC at $\text{GWL} = 4\text{ }^{\circ}\text{C}$ while five models clearly show a significant positive ZEC at this GWL that is more positive than the value at $\text{GWL} = 2\text{ }^{\circ}\text{C}$).



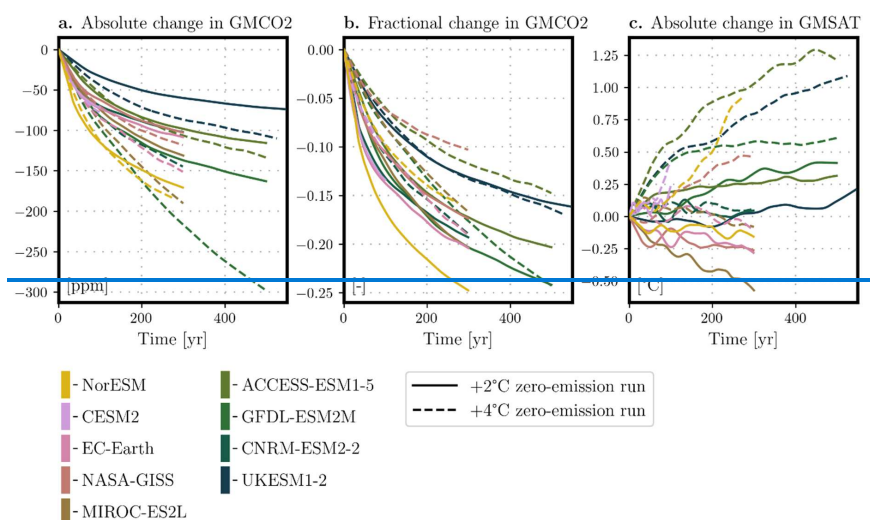


Figure 4: Change in global mean atmospheric CO₂ concentration and GMSAT for the two zero-emission runs expressed as anomalies relative to each value at the start of the respective zero-emission run. Left panel: absolute change in atm.CO₂ in ppm, middle panel: fractional change in atm. CO₂, and right 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.

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 CO₂-emission mode (i.e. full carbon cycle with atmospheric CO₂ a prognostic model variable). The protocol requires a constant emission of CO₂, 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), CO₂-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, CO₂-emissions are set to the negative of the positive emission rate used in the warming-ramp-up-run. These two negative CO₂-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 $\text{GWL} = 4^\circ\text{C}$ first drops below $\text{GWL} = 2^\circ\text{C}$ a zero-emission run is branched off this, completing the Tier 1 set of experiments.

While this experiment protocol is highly idealized (using only CO_2 emissions as a surrogate for all anthropogenic forcing), the resulting ensemble can be used to investigate (i) the risks, consequences, and drivers of abrupt/rapid Earth system change (tipping points) under net zero CO_2 emission, initiated at different global warming levels, (ii) the long-term response of the Earth system to net zero CO_2 emissions, (iii) the behaviour of the Earth system under prescribed net negative CO_2 emissions following a specified (magnitude and duration) of global warming overshoot, (iv) the efficacy of net negative CO_2 emissions in driving global cooling, and (v) the reversibility of Earth system change under a pathway of positive (warming), zero (near stabilization), and negative (cooling) CO_2 emissions. The primary advantage of the protocol is that we can control the rate of global warming and (potentially) 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 near common global warming/cooling space. 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, and with a common set of diagnostics will be being archived to the Earth System Grid Federation (ESGF), initially following the CMIP6plus protocol. This paper is to facilitate the TIPMIP ESM experiments 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 CO_2 (atm.CO_2). 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> (Licon-Salaiz, 2025).

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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); [“Progressing Earth System Modelling for Tipping Point Early Warning Systems”](#), PROMOTE (Grant number SCOP-PRO1-P027), part of the [Forecasting Tipping Points programme of the Advanced Research + Invention Agency \(ARIA\)](#); 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 ANtctica: 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 & 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.

References

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N.: Warming caused by cumulative carbon emissions towards the trillionth tonne, *Nature*, 458, 1163–1166, <https://doi.org/10.1038/nature08019>, 2009.

940 Allen, M. R., Friedlingstein, P., Girardin, C. A. J., Jenkins, S., Malhi, Y., Mitchell-Larson, E., Peters, G. P., and Rajamani, L.: Net Zero: Science, Origins, and Implications, *Annu. Rev. Environ. Resour.*, 47, 849–887, <https://doi.org/10.1146/annurev-environ-112320-105050>, 2022.

Andrews, T., Andrews, M. B., Bodas-Salcedo, A., Jones, G. S., Kuhlbrodt, T., Manners, J., Menary, M. B., Ridley, J., Ringer, M. A., Sellar, A. A., Senior, C. A., and Tang, Y.: Forcings, Feedbacks, and Climate Sensitivity in HadGEM3-GC3.1 and UKESM1, *J Adv Model Earth Syst*, 11, 4377–4394, <https://doi.org/10.1029/2019ms001866>, 2019.

945 Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., and Lenton, T. M.: Exceeding 1.5°C global warming could trigger multiple climate tipping points, *Science*, 377, <https://doi.org/10.1126/science.abn7950>, 2022.

Arora, V. K., Katavouta, A., Williams, R. G., Jones, C. D., Brovkin, V., Friedlingstein, P., Schwinger, J., Bopp, L., Boucher, O., Cadule, P., Chamberlain, M. A., Christian, J. R., Delire, C., Fisher, R. A., Hajima, T., Ilyina, T., Joetzjer, E., Kawamiya, M., Koven, C. D., Krasting, J. P., Law, R. M., Lawrence, D. M., Lenton, A., Lindsay, K., Pongratz, J., Raddatz, T., Séférian, R., Tachiiri, K., Tjiputra, J. F., Wiltshire, A., Wu, T., and Ziehn, T.: Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their comparison to CMIP5 models, *Biogeosciences*, 17, 4173–4222, <https://doi.org/10.5194/bg-17-4173-2020>, 2020.

955 Asaadi, A., Schwinger, J., Lee, H., Tjiputra, J., Arora, V., Séférian, R., Liddicoat, S., Hajima, T., Santana-Falcón, Y., and Jones, C. D.: Carbon cycle feedbacks in an idealized simulation and a scenario simulation of negative emissions in CMIP6 Earth system models, *Biogeosciences*, 21, 411–435, <https://doi.org/10.5194/bg-21-411-2024>, 2024.

Ben-Yami, M., Good, P., Jackson, L. C., Crucifix, M., Hu, A., Saenko, O., Swingedouw, D., and Boers, N.: Impacts of AMOC Collapse on Monsoon Rainfall: A Multi-Model Comparison, *Earth’s Future*, 12, <https://doi.org/10.1029/2023ef003959>, 2024.

960 Bertini, L. and Tjiputra, J.: Biogeochemical Timescales of Climate Change Onset and Recovery in the North Atlantic Interior Under Rapid Atmospheric CO₂ Forcing, *JGR Oceans*, 127, <https://doi.org/10.1029/2021jc017929>, 2022.

Bochow, N. and Boers, N.: The South American monsoon approaches a critical transition in response to deforestation, *Sci. Adv.*, 9, <https://doi.org/10.1126/sciadv.add9973>, 2023.

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Boers, N., Marwan, N., Barbosa, H. M. J., and Kurths, J.: A deforestation-induced tipping point for the South American monsoon system, *Sci Rep*, 7, <https://doi.org/10.1038/srep41489>, 2017.

Booth, B. B. B., Jones, C. D., Collins, M., Totterdell, I. J., Cox, P. M., Sitch, S., Huntingford, C., Betts, R. A., Harris, G. R., and Lloyd, J.: High sensitivity of future global warming to land carbon cycle processes, *Environ. Res. Lett.*, 7, 024002, <https://doi.org/10.1088/1748-9326/7/2/024002>, 2012.

Bossert, I.: The TIPMIP Earth system model experiment protocol: phase1- datasets for Figures 2, 3 and 4: v1 (v1), Zenodo [code and dataset], <https://zenodo.org/17055322>, 2025.

Boulton, C. A., Lenton, T. M., and Boers, N.: Pronounced loss of Amazon rainforest resilience since the early 2000s, *Nat. Clim. Chang.*, 12, 271–278, <https://doi.org/10.1038/s41558-022-01287-8>, 2022.

Burke, E. J., Zhang, Y., and Krinner, G.: Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change, *The Cryosphere*, 14, 3155–3174, <https://doi.org/10.5194/tc-14-3155-2020>, 2020.

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., and Saba, V.: Observed fingerprint of a weakening Atlantic Ocean overturning circulation, *Nature*, 556, 191–196, <https://doi.org/10.1038/s41586-018-0006-5>, 2018.

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., and Rahmstorf, S.: Current Atlantic Meridional Overturning Circulation weakest in last millennium, *Nat. Geosci.*, 14, 118–120, <https://doi.org/10.1038/s41561-021-00699-z>, 2021.

Cassidy, L. J., King, A. D., Brown, J. R., MacDougall, A. H., Ziehn, T., Min, S.-K., and Jones, C. D.: Regional temperature extremes and vulnerability under net zero CO₂ emissions, *Environ. Res. Lett.*, 19, 014051, <https://doi.org/10.1088/1748-9326/ad114a>, 2024.

Chamberlain, M. A., Ziehn, T., and Law, R. M.: The Southern Ocean as the climate’s freight train – driving ongoing global warming under zero-emission scenarios with ACCESS-ESM1.5, *Biogeosciences*, 21, 3053–3073, <https://doi.org/10.5194/bg-21-3053-2024>, 2024.

Chapman, R., Sinet, S., and Ritchie, P. D. L.: Tipping mechanisms in a conceptual model of the Atlantic Meridional Overturning Circulation, *Weather*, 79, 316–323, <https://doi.org/10.1002/wea.7609>, 2024.

Chen, X. and Tung, K.-K.: Global surface warming enhanced by weak Atlantic overturning circulation, *Nature*, 559, 387–391, <https://doi.org/10.1038/s41586-018-0320-y>, 2018.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, 408, 184–187, <https://doi.org/10.1038/35041539>, 2000.

Da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Santos, S. R., and Schwartz, G.: An overview of forest loss and restoration in the Brazilian Amazon, *New Forests*, 52, 1–16, <https://doi.org/10.1007/s11056-020-09777-3>, 2021.

De Vrese, P. and Brovkin, V.: Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios, *Nat Commun*, 12, <https://doi.org/10.1038/s41467-021-23010-5>, 2021.

Defrance, D., Ramstein, G., Charbit, S., Vrac, M., Famién, A. M., Sultan, B., Swingedouw, D., Dumas, C., Gemenne, F., Alvarez-Solas, J., and Vanderlinden, J.-P.: Consequences of rapid ice sheet melting on the Sahelian population vulnerability,

Proc. Natl. Acad. Sci. U.S.A., 114, 6533–6538, <https://doi.org/10.1073/pnas.1619358114>, 2017.

DeVries, T., Holzer, M., and Primeau, F.: Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning, *Nature*, 542, 215–218, <https://doi.org/10.1038/nature21068>, 2017.

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G., and Swingedouw, D.: Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models, *Proc. Natl. Acad. Sci. U.S.A.*, 112, <https://doi.org/10.1073/pnas.1511451112>, 2015.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Sentman, L. T., Adcroft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, R. W., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J., and Zadeh, N.: GFDL’s ESM2 Global Coupled Climate–Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics*, *Journal of Climate*, 26, 2247–2267, <https://doi.org/10.1175/jcli-d-12-00150.1>, 2013.

Dunne, J. P., Hewitt, H. T., Arblaster, J. M., Bonou, F., Boucher, O., Cavazos, T., Dingley, B., Durack, P. J., Hassler, B., Jukes, M., Miyakawa, T., Mizielinski, M., Naik, V., Nicholls, Z., O’Rourke, E., Pincus, R., Sanderson, B. M., Simpson, I. R., and Taylor, K. E.: An evolving Coupled Model Intercomparison Project phase 7 (CMIP7) and Fast Track in support of future climate assessment, *Geosci. Model Dev.*, 18, 6671–6700, <https://doi.org/10.5194/gmd-18-6671-2025>, 2025.

Evin, G., Ribes, A., and Corre, L.: Assessing CMIP6 uncertainties at global warming levels, *Clim Dyn*, 62, 8057–8072, <https://doi.org/10.1007/s00382-024-07323-x>, 2024.

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., and Wetzler, T.: The meaning of net zero and how to get it right, *Nat. Clim. Chang.*, 12, 15–21, <https://doi.org/10.1038/s41558-021-01245-w>, 2022.

Feldmann, J. and Levermann, A.: Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin, *Proc. Natl. Acad. Sci. U.S.A.*, 112, 14191–14196, <https://doi.org/10.1073/pnas.1512482112>, 2015.

Fischer, E. M., Sippel, S., and Knutti, R.: Increasing probability of record-shattering climate extremes, *Nat. Clim. Chang.*, 11, 689–695, <https://doi.org/10.1038/s41558-021-01092-9>, 2021.

Flores, B. M., Montoya, E., Sakschewski, B., Nascimento, N., Staal, A., Betts, R. A., Levis, C., Lapola, D. M., Esquivel-Muelbert, A., Jakovac, C., Nobre, C. A., Oliveira, R. S., Borma, L. S., Nian, D., Boers, N., Hecht, S. B., Ter Steege, H., Arieira, J., Lucas, I. L., Berenguer, E., Marengo, J. A., Gatti, L. V., Mattos, C. R. C., and Hirota, M.: Critical transitions in the Amazon forest system, *Nature*, 626, 555–564, <https://doi.org/10.1038/s41586-023-06970-0>, 2024.

Fons, E., Runge, J., Neubauer, D., and Lohmann, U.: Stratocumulus adjustments to aerosol perturbations disentangled with a causal approach, *npj Clim Atmos Sci*, 6, <https://doi.org/10.1038/s41612-023-00452-w>, 2023.

Franzke, C. L. E., Ciullo, A., Gilmore, E. A., Matias, D. M., Nagabhatla, N., Orlov, A., Paterson, S. K., Scheffran, J., and Sillmann, J.: Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling, *Environ. Res. Lett.*, 17, 015004, <https://doi.org/10.1088/1748-9326/ac42fd>, 2022.

Fraser, N. J. and Cunningham, S. A.: 120 Years of AMOC Variability Reconstructed From Observations Using the Bernoulli

Inverse, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2021gl093893>, 2021.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Lujikx, J. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Armeth, A., Arora, V., Bates, N. R., Becker, M., Bellouin, N., Berghoff, C. F., Bittig, H. C., Bopp, L., Cadule, P., Campbell, K., Chamberlain, M. A., Chandra, N., Chevallier, F., Chini, L. P., Colligan, T., Decayeux, J., Djeutchouang, L. M., Dou, X., Duran Rojas, C., Enyo, K., Evans, W., Fay, A. R., Feely, R. A., Ford, D. J., Foster, A., Gasser, T., Gehlen, M., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Hurtt, G. C., Iida, Y., Ilyina, T., Jacobson, A. R., Jain, A. K., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Kato, E., Keeling, R. F., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Lan, X., Lauvset, S. K., Lefèvre, N., Liu, Z., Liu, J., Ma, L., Maksyutov, S., Marland, G., Mayot, N., McGuire, P. C., Metzl, N., Monacci, N. M., Morgan, E. J., Nakaoka, S.-I., Neill, C., Niwa, Y., Nützel, T., Olivier, L., Ono, T., Palmer, P. I., Pierrot, D., Qin, Z., Resplandy, L., Roobaert, A., Rosan, T. M., Rödenbeck, C., Schwinger, J., Smallman, T. L., Smith, S. M., Sospedra-Alfonso, R., Steinhoff, T., et al.: Global Carbon Budget 2024, *Earth Syst. Sci. Data*, 17, 965–1039, <https://doi.org/10.5194/essd-17-965-2025>, 2025.

Frieler, K., Volkholz, J., Lange, S., Schewe, J., Mengel, M., Del Rocio Rivas López, M., Otto, C., Reyer, C. P. O., Karger, D. N., Malle, J. T., Treu, S., Menz, C., Blanchard, J. L., Harrison, C. S., Petrik, C. M., Eddy, T. D., Ortega-Cisneros, K., Novaglio, C., Rousseau, Y., Watson, R. A., Stock, C., Liu, X., Heneghan, R., Tittensor, D., Maury, O., Büchner, M., Vogt, T., Wang, T., Sun, F., Sauer, I. J., Koch, J., Vanderkelen, I., Jägermeyr, J., Müller, C., Rabin, S., Klar, J., Vega Del Valle, I. D., Lasslop, G., Chadburn, S., Burke, E., Gallego-Sala, A., Smith, N., Chang, J., Hantson, S., Burton, C., Gädeke, A., Li, F., Gosling, S. N., Müller Schmied, H., Hattermann, F., Wang, J., Yao, F., Hickler, T., Marcé, R., Pierson, D., Thiery, W., Mercado-Bettín, D., Ladwig, R., Ayala-Zamora, A. I., Forrest, M., and Bechtold, M.: Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3a), *Geosci. Model Dev.*, 17, 1–51, <https://doi.org/10.5194/gmd-17-1-2024>, 2024.

Fröb, F., Bourgeois, T., Goris, N., Schwinger, J., and Heinze, C.: Simulated Abrupt Shifts in Aerobic Habitats of Marine Species in the Past, Present, and Future, *Earth's Future*, 12, <https://doi.org/10.1029/2023ef004141>, 2024.

Frölicher, T. L. and Paynter, D. J.: Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales, *Environ. Res. Lett.*, 10, 075002, <https://doi.org/10.1088/1748-9326/10/7/075002>, 2015.

Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., and Winkelmann, R.: The hysteresis of the Antarctic Ice Sheet, *Nature*, 585, 538–544, <https://doi.org/10.1038/s41586-020-2727-5>, 2020.

Gerten, D., Lucht, W., Ostberg, S., Heinke, J., Kowarsch, M., Kreft, H., Kundzewicz, Z. W., Rastgooy, J., Warren, R., and Schellnhuber, H. J.: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems, *Environ. Res. Lett.*, 8, 034032, <https://doi.org/10.1088/1748-9326/8/3/034032>, 2013.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., Van Vuuren, D. P., Van Den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., and Takahashi, K.: Global emissions pathways under different socioeconomic scenarios for

use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, *Geosci. Model Dev.*, 12, 1443–1475, <https://doi.org/10.5194/gmd-12-1443-2019>, 2019.

Gillett, N. P., Arora, V. K., Matthews, D., and Allen, M. R.: Constraining the Ratio of Global Warming to Cumulative CO₂ Emissions Using CMIP5 Simulations*, *Journal of Climate*, 26, 6844–6858, <https://doi.org/10.1175/jcli-d-12-00476.1>, 2013.

1070 Gillett, N. P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G. C., Knutti, R., Gastineau, G., John, J. G., Li, L., Nazarenko, L., Rosenbloom, N., Seland, Ø., Wu, T., Yukimoto, S., and Ziehn, T.: Constraining human contributions to observed warming since the pre-industrial period, *Nat. Clim. Chang.*, 11, 207–212, <https://doi.org/10.1038/s41558-020-00965-9>, 2021.

Golledge, N. R., Levy, R. H., McKay, R. M., and Naish, T. R.: East Antarctic ice sheet most vulnerable to Weddell Sea warming, *Geophysical Research Letters*, 44, 2343–2351, <https://doi.org/10.1002/2016gl072422>, 2017.

1075 Good, P., Jones, C., Lowe, J., Betts, R., Booth, B., and Huntingford, C.: Quantifying Environmental Drivers of Future Tropical Forest Extent, *Journal of Climate*, 24, 1337–1349, <https://doi.org/10.1175/2010jcli3865.1>, 2011.

Gregory, J. M., George, S. E., and Smith, R. S.: Large and irreversible future decline of the Greenland ice sheet, *The Cryosphere*, 14, 4299–4322, <https://doi.org/10.5194/tc-14-4299-2020>, 2020.

1080 Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döschner, R., Gehlen, M., Gruber, N., Holland, E., Hov, Ø., Joos, F., Matthews, J. B. R., Rødven, R., and Wilson, S.: The quiet crossing of ocean tipping points, *Proc. Natl. Acad. Sci. U.S.A.*, 118, <https://doi.org/10.1073/pnas.2008478118>, 2021.

Heinze, C., Blenckner, T., Brown, P., Fröb, F., Morée, A., New, A. L., Nissen, C., Rynders, S., Seguro, I., Aksenov, Y., Artioli, Y., Bourgeois, T., Burger, F., Buzan, J., Cael, B. B., Yumruktepe, V. Ç., Chierici, M., Danek, C., Dieckmann, U., Fransson, A., Frölicher, T., Galli, G., Gehlen, M., González, A. G., Gonzalez-Davila, M., Gruber, N., Gustafsson, Ö., Hauck, J., Heino, M., Henson, S., Hieronymus, J., Huertas, I. E., Jebri, F., Jeltsch-Thömmes, A., Joos, F., Joshi, J., Kelly, S., Menon, N., Mongwe, P., Oziel, L., Ólafsdóttir, S., Palmieri, J., Pérez, F. F., Ranith, R. P., Ramanantsoa, J., Roy, T., Rusiecka, D., Santana Casiano, J. M., Santana-Falcón, Y., Schwinger, J., Séférian, R., Seifert, M., Shchiptsova, A., Sinha, B., Somes, C., Steinfeldt, R., Tao, D., Tjiputra, J., Ulfssbo, A., Völker, C., Wakamatsu, T., and Ye, Y.: Reviews and syntheses: Abrupt ocean biogeochemical change under human-made climatic forcing – warming, acidification, and deoxygenation, <https://doi.org/10.5194/bg-2023-182>, 10 October 2023.

1090 Held, I. M., Winton, M., Takahashi, K., Delworth, T., Zeng, F., and Vallis, G. K.: Probing the Fast and Slow Components of Global Warming by Returning Abruptly to Preindustrial Forcing, *Journal of Climate*, 23, 2418–2427, <https://doi.org/10.1175/2009jcli3466.1>, 2010.

1095 Heuzé, C. and Jahn, A.: The first ice-free day in the Arctic Ocean could occur before 2030, *Nat Commun.*, 15, <https://doi.org/10.1038/s41467-024-54508-3>, 2024.

Höning, D., Willeit, M., Calov, R., Klemann, V., Bagge, M., and Ganopolski, A.: Multistability and Transient Response of the Greenland Ice Sheet to Anthropogenic CO₂ Emissions, *Geophysical Research Letters*, 50, <https://doi.org/10.1029/2022gl101827>, 2023.

- 1100 [Horton, D. E., Johnson, N. C., Singh, D., Swain, D. L., Rajaratnam, B., and Diffenbaugh, N. S.: Contribution of changes in atmospheric circulation patterns to extreme temperature trends, *Nature*, 522, 465–469, <https://doi.org/10.1038/nature14550>, 2015.](#)
- [Hu, A., Otto-Bliesner, B. L., Meehl, G. A., Han, W., Morrill, C., Brady, E. C., and Briegleb, B.: Response of Thermohaline Circulation to Freshwater Forcing under Present-Day and LGM Conditions, *Journal of Climate*, 21, 2239–2258, <https://doi.org/10.1175/2007jcli1985.1>, 2008.](#)
- 1105 [IPCC: The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press, <https://doi.org/10.1017/9781009157964>, 2022a.](#)
- [IPCC: Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, 1st ed., Cambridge University Press, <https://doi.org/10.1017/9781009157940>, 2022b.](#)
- 1110 [IPCC: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press, <https://doi.org/10.1017/9781009157896>, 2023a.](#)
- [IPCC: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland., <https://doi.org/10.59327/ipcc/ar6-9789291691647.001>, 2023b.](#)
- 1115 [Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., and Wood, R. A.: Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, *Clim Dyn*, 45, 3299–3316, <https://doi.org/10.1007/s00382-015-2540-2>, 2015.](#)
- 1120 [Jackson, L. C., Alastrué De Asenjo, E., Bellomo, K., Danabasoglu, G., Haak, H., Hu, A., Jungclaus, J., Lee, W., Meccia, V. L., Saenko, O., Shao, A., and Swingedouw, D.: Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project, *Geosci. Model Dev.*, 16, 1975–1995, <https://doi.org/10.5194/gmd-16-1975-2023>, 2023.](#)
- [Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D. E., Coscieme, L., Golden, A. S., Guerra, C. A., Jacob, U., Takahashi, Y., Settele, J., Díaz, S., Molnár, Z., and Purvis, A.: The direct drivers of recent global anthropogenic biodiversity loss, *Sci. Adv.*, 8, <https://doi.org/10.1126/sciadv.abm9982>, 2022.](#)
- 1125 [Jeltsch-Thömmes, A., Stocker, T. F., and Joos, F.: Hysteresis of the Earth system under positive and negative CO₂ emissions, *Environ. Res. Lett.*, 15, 124026, <https://doi.org/10.1088/1748-9326/abc4af>, 2020.](#)
- [Jensen, L., Gerdener, H., Eicker, A., Kusche, J., and Fiedler, S.: Observations indicate regionally misleading wetting and drying trends in CMIP6, *npj Clim Atmos Sci*, 7, <https://doi.org/10.1038/s41612-024-00788-x>, 2024.](#)
- 1130 [Jones, C. D. and Friedlingstein, P.: Quantifying process-level uncertainty contributions to TCRE and carbon budgets for meeting Paris Agreement climate targets, *Environmental Research Letters*, 15, 074019, <https://doi.org/10.1088/1748-9326/ab858a>, 2020.](#)
- [Jones, C. D., Ciais, P., Davis, S. J., Friedlingstein, P., Gasser, T., Peters, G. P., Rogelj, J., Van Vuuren, D. P., Canadell, J. G.,](#)

Cowie, A., Jackson, R. B., Jonas, M., Kriegler, E., Littleton, E., Lowe, J. A., Milne, J., Shrestha, G., Smith, P., Torvanger, A., and Wiltshire, A.: Simulating the Earth system response to negative emissions, *Environ. Res. Lett.*, 11, 095012, <https://doi.org/10.1088/1748-9326/11/9/095012>, 2016.

Jones, C. D., Frölicher, T. L., Koven, C., MacDougall, A. H., Matthews, H. D., Zickfeld, K., Rogelj, J., Tokarska, K. B., Gillett, N. P., Ilyina, T., Meinshausen, M., Mengis, N., Séférian, R., Eby, M., and Burger, F. A.: The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions, *Geosci. Model Dev.*, 12, 4375–4385, <https://doi.org/10.5194/gmd-12-4375-2019>, 2019.

Licon-Salaiz, J.: `tipmip-methods/tipmip-data-req: v1.1.1 (v1.1.1)`. Zenodo [data request], <https://doi.org/10.5281/zenodo.15189530>, 2025.

Keller, D. P., Lenton, A., Scott, V., Vaughan, N. E., Bauer, N., Ji, D., Jones, C. D., Kravitz, B., Muri, H., and Zickfeld, K.: The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6, *Geosci. Model Dev.*, 11, 1133–1160, <https://doi.org/10.5194/gmd-11-1133-2018>, 2018.

Kilbourne, K. H., Wanamaker, A. D., Moffa-Sanchez, P., Reynolds, D. J., Amrhein, D. E., Butler, P. G., Gebbie, G., Goes, M., Jansen, M. F., Little, C. M., Mette, M., Moreno-Chamorro, E., Ortega, P., Otto-Bliesner, B. L., Rossby, T., Scourse, J., and Whitney, N. M.: Atlantic circulation change still uncertain, *Nat. Geosci.*, 15, 165–167, <https://doi.org/10.1038/s41561-022-00896-4>, 2022.

Kim, S.-K. and An, S.-I.: Emergence of a climate oscillation in the Arctic Ocean due to global warming, *Nat. Clim. Chang.*, 14, 1268–1274, <https://doi.org/10.1038/s41558-024-02171-3>, 2024.

King, A. D., Lane, T. P., Henley, B. J., and Brown, J. R.: Global and regional impacts differ between transient and equilibrium warmer worlds, *Nat. Clim. Chang.*, 10, 42–47, <https://doi.org/10.1038/s41558-019-0658-7>, 2020.

King, A. D., Sniderman, J. M. K., Dittus, A. J., Brown, J. R., Hawkins, E., and Ziehn, T.: Studying climate stabilization at Paris Agreement levels, *Nat. Clim. Chang.*, 11, 1010–1013, <https://doi.org/10.1038/s41558-021-01225-0>, 2021.

King, A. D., Ziehn, T., Chamberlain, M., Borowiak, A. R., Brown, J. R., Cassidy, L., Dittus, A. J., Grose, M., Maher, N., Paik, S., Perkins-Kirkpatrick, S. E., and Sengupta, A.: Exploring climate stabilisation at different global warming levels in ACCESS-ESM-1.5, *Earth Syst. Dynam.*, 15, 1353–1383, <https://doi.org/10.5194/esd-15-1353-2024>, 2024.

Kjellström, E., Nikulin, G., Strandberg, G., Christensen, O. B., Jacob, D., Keuler, K., Lenderink, G., Van Meijgaard, E., Schär, C., Somot, S., Sørland, S. L., Teichmann, C., and Vautard, R.: European climate change at global mean temperature increases of 1.5 and 2 °C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models, *Earth Syst. Dynam.*, 9, 459–478, <https://doi.org/10.5194/esd-9-459-2018>, 2018.

Klose, A. K., Karle, V., Winkelmann, R., and Donges, J. F.: Emergence of cascading dynamics in interacting tipping elements of ecology and climate, *R. Soc. open sci.*, 7, 200599, <https://doi.org/10.1098/rsos.200599>, 2020.

Klose, A. K., Donges, J. F., Feudel, U., and Winkelmann, R.: Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation, *Earth Syst. Dynam.*, 15, 635–652, <https://doi.org/10.5194/esd-15-635-2024>, 2024.

Formatted: Space After: 0 pt, Line spacing: 1.5 lines

- Koenigk, T., Bähring, L., Matei, D., Nikulin, G., Strandberg, G., Tyrlis, E., Wang, S., and Wilcke, R.: On the contribution of internal climate variability to European future climate trends, *Tellus A: Dynamic Meteorology and Oceanography*, 72, 1788901, <https://doi.org/10.1080/16000870.2020.1788901>, 2020.
- Koven, C. D.: Boreal carbon loss due to poleward shift in low-carbon ecosystems, *Nature Geosci.*, 6, 452–456, <https://doi.org/10.1038/ngeo1801>, 2013.
- Koven, C. D., Arora, V. K., Cadule, P., Fisher, R. A., Jones, C. D., Lawrence, D. M., Lewis, J., Lindsay, K., Mathesius, S., Meinshausen, M., Mills, M., Nicholls, Z., Sanderson, B. M., Séférian, R., Swart, N. C., Wieder, W. R., and Zickfeld, K.: Multi-century dynamics of the climate and carbon cycle under both high and net negative emissions scenarios, *Earth Syst. Dynam.*, 13, 885–909, <https://doi.org/10.5194/esd-13-885-2022>, 2022.
- Koven, C. D., Sanderson, B. M., and Swann, A. L. S.: Much of zero emissions commitment occurs before reaching net zero emissions, *Environ. Res. Lett.*, 18, 014017, <https://doi.org/10.1088/1748-9326/acab1a>, 2023.
- Krasting, J. P., Dunne, J. P., Shevliakova, E., and Stouffer, R. J.: Trajectory sensitivity of the transient climate response to cumulative carbon emissions, *Geophys. Res. Lett.*, 41, 2520–2527, <https://doi.org/10.1002/2013gl059141>, 2014.
- Kubelka, V., Sandercock, B. K., Székely, T., and Freckleton, R. P.: Animal migration to northern latitudes: environmental changes and increasing threats, *Trends in Ecology & Evolution*, 37, 30–41, <https://doi.org/10.1016/j.tree.2021.08.010>, 2022.
- Kug, J.-S., Oh, J.-H., An, S.-I., Yeh, S.-W., Min, S.-K., Son, S.-W., Kam, J., Ham, Y.-G., and Shin, J.: Hysteresis of the intertropical convergence zone to CO₂ forcing, *Nat. Clim. Chang.*, 12, 47–53, <https://doi.org/10.1038/s41558-021-01211-6>, 2022.
- Lacroix, F., Burger, F. A., Silvy, Y., Schleussner, C., and Frölicher, T. L.: Persistently Elevated High-Latitude Ocean Temperatures and Global Sea Level Following Temporary Temperature Overshoots, *Earth's Future*, 12, <https://doi.org/10.1029/2024ef004862>, 2024.
- Lennard, C. J., Nikulin, G., Dosio, A., and Moufouma-Okia, W.: On the need for regional climate information over Africa under varying levels of global warming, *Environ. Res. Lett.*, 13, 060401, <https://doi.org/10.1088/1748-9326/aab2b4>, 2018.
- Lenton, T. M.: Arctic Climate Tipping Points, *AMBIO*, 41, 10–22, <https://doi.org/10.1007/s13280-011-0221-x>, 2012.
- Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, *Proc. Natl. Acad. Sci. U.S.A.*, 105, 1786–1793, <https://doi.org/10.1073/pnas.0705414105>, 2008.
- Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., and Schellnhuber, H. J.: Climate tipping points — too risky to bet against, *Nature*, 575, 592–595, <https://doi.org/10.1038/d41586-019-03595-0>, 2019.
- Lenton, T. M., Armstrong McKay, D.I., Loriani, S., Abrams, J.F., Lade, S.J., Donges, J.F., Milkoreit, M., Powell, T., Smith, S.R., Zimm, C., Buxton, J.E., Bailey, E., Laybourn, L., Ghadiali, A., Dyke, J.G. (eds): *The Global Tipping Points Report 2023*, University of Exeter, Exeter, UK, 2023.
- Lenton, T. M., Abrams, J. F., Bartsch, A., Bathiany, S., Boulton, C. A., Buxton, J. E., Conversi, A., Cunliffe, A. M., Hebden, S., Lavergne, T., Poulter, B., Shepherd, A., Smith, T., Swingedouw, D., Winkelmann, R., and Boers, N.: Remotely sensing potential climate change tipping points across scales, *Nat Commun.*, 15, <https://doi.org/10.1038/s41467-023-44609-w>, 2024.

- Lenton, T. M., Milkoreit, M., Willcock, S., Abrams, J. F., Armstrong, McKay, D. I., Buxton, J. E., Donges, J. F., Loriani, S., Wunderling, N., Alkemade, F., Barrett, M., Constantino, S., Powell, T., Smith, S. R., and Boulton, C. A., Pinho, P., Dijkstra, H. A., Pearce-Kelly, P., Roman Cuesta, R. M., Dennis, D. (eds), 2: The Global Tipping Points Report 2025, University of Exeter, Exeter, UK, 2025.
- Levermann, A. and Winkelmann, R.: A simple equation for the melt elevation feedback of ice sheets, *The Cryosphere*, 10, 1799–1807, <https://doi.org/10.5194/tc-10-1799-2016>, 2016.
- Levermann, A., Clark, P. U., Marzeion, B., Milne, G. A., Pollard, D., Radic, V., and Robinson, A.: The multimillennial sea-level commitment of global warming, *Proc. Natl. Acad. Sci. U.S.A.*, 110, 13745–13750, <https://doi.org/10.1073/pnas.1219414110>, 2013.
- Li, S., Huang, G., Li, X., Liu, J., and Fan, G.: An Assessment of the Antarctic Sea Ice Mass Budget Simulation in CMIP6 Historical Experiment, *Front. Earth Sci.*, 9, <https://doi.org/10.3389/feart.2021.649743>, 2021.
- Litzow, M. A. and Hunsicker, M. E.: Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems, *Ecosphere*, 7, <https://doi.org/10.1002/ecs2.1614>, 2016.
- Liu, W., Fedorov, A. V., Xie, S.-P., and Hu, S.: Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate, *Sci. Adv.*, 6, <https://doi.org/10.1126/sciadv.aaz4876>, 2020.
- Liu-Helmersson, J., Stenlund, H., Wilder-Smith, A., and Rocklöv, J.: Vectorial Capacity of *Aedes aegypti*: Effects of Temperature and Implications for Global Dengue Epidemic Potential, *PLoS ONE*, 9, e89783, <https://doi.org/10.1371/journal.pone.0089783>, 2014.
- Lovejoy, T. E. and Nobre, C.: Amazon Tipping Point, *Sci. Adv.*, 4, <https://doi.org/10.1126/sciadv.aat2340>, 2018.
- MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra, J., Wiltshire, A., and Ziehn, T.: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO₂, *Biogeosciences*, 17, 2987–3016, <https://doi.org/10.5194/bg-17-2987-2020>, 2020.
- Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K.: The proportionality of global warming to cumulative carbon emissions, *Nature*, 459, 829–832, <https://doi.org/10.1038/nature08047>, 2009.
- McCarthy, G. D. and Caesar, L.: Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past?, *Phil. Trans. R. Soc. A*, 381, <https://doi.org/10.1098/rsta.2022.0193>, 2023.
- Mecking, J. V., Drijfhout, S. S., Jackson, L. C., and Andrews, M. B.: The effect of model bias on Atlantic freshwater transport and implications for AMOC bi-stability, *Tellus A: Dynamic Meteorology and Oceanography*, 69, 1299910, <https://doi.org/10.1080/16000870.2017.1299910>, 2017.
- Menary, M. B., Robson, J., Allan, R. P., Booth, B. B. B., Cassou, C., Gastineau, G., Gregory, J., Hodson, D., Jones, C., Mignot, J., Ringer, M., Sutton, R., Wilcox, L., and Zhang, R.: Aerosol-Forced AMOC Changes in CMIP6 Historical Simulations, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2020gl088166>, 2020.

Myksovoll, M. S., Britt Sandø, A., Tijputra, J., Samuelsen, A., Çağlar Yumruketepe, V., Li, C., Mousing, E. A., Bettencourt, J. P. H., and Ottersen, G.: Key physical processes and their model representation for projecting climate impacts on subarctic Atlantic net primary production: A synthesis, *Progress in Oceanography*, 217, 103084, <https://doi.org/10.1016/j.pcean.2023.103084>, 2023.

1240 Natali, S. M., Holdren, J. P., Rogers, B. M., Treharne, R., Duffy, P. B., Pomerance, R., and MacDonald, E.: Permafrost carbon feedbacks threaten global climate goals, *Proc. Natl. Acad. Sci. U.S.A.*, 118, <https://doi.org/10.1073/pnas.2100163118>, 2021.

Naughten, K. A., Holland, P. R., and De Rydt, J.: Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century, *Nat. Clim. Chang.*, 13, 1222–1228, <https://doi.org/10.1038/s41558-023-01818-x>, 2023.

1245 Nitzbon, J., Schneider Von Deimling, T., Aliyeva, M., Chadburn, S. E., Grosse, G., Laboor, S., Lee, H., Lohmann, G., Steinert, N. J., Stuenzi, S. M., Werner, M., Westermann, S., and Langer, M.: No respite from permafrost-thaw impacts in the absence of a global tipping point, *Nat. Clim. Chang.*, 14, 573–585, <https://doi.org/10.1038/s41558-024-02011-4>, 2024.

Noël, B., Van Kampenhout, L., Lenaerts, J. T. M., Van De Berg, W. J., and Van Den Broeke, M. R.: A 21st Century Warming Threshold for Sustained Greenland Ice Sheet Mass Loss, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2020gl090471>, 2021.

1250 Notz, D. and Community, S.: Arctic Sea Ice in CMIP6, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2019gl086749>, 2020.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, *Geosci. Model Dev.*, 9, 3461–3482, <https://doi.org/10.5194/gmd-9-3461-2016>, 2016.

1255 Parry, I. M., Ritchie, P. D. L., and Cox, P. M.: Evidence of localised Amazon rainforest dieback in CMIP6 models, *Earth Syst. Dynam.*, 13, 1667–1675, <https://doi.org/10.5194/esd-13-1667-2022>, 2022.

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., Kuipers Munneke, P., Lenaerts, J. T. M., Nowicki, S., Payne, A. J., Robinson, A., Seroussi, H., Trusel, L. D., and Van Den Broeke, M.: The Greenland and Antarctic ice sheets under 1.5 °C global warming, *Nature Clim Change*, 8, 1053–1061, <https://doi.org/10.1038/s41558-018-0305-8>, 2018.

1260 Portmann, V., Chavent, M., and Swingedouw, D.: ClimLoco1.0: CLimate variable confidence Interval of Multivariate Linear Observational CONstraint, <https://doi.org/10.5194/egusphere-2025-62>, 24 January 2025.

Randerson, J. T., Lindsay, K., Munoz, E., Fu, W., Moore, J. K., Hoffman, F. M., Mahowald, N. M., and Doney, S. C.: Multicentury changes in ocean and land contributions to the climate-carbon feedback, *Global Biogeochemical Cycles*, 29, 744–759, <https://doi.org/10.1002/2014gb005079>, 2015.

1265 Raupach, M. R., Gloor, M., Sarmiento, J. L., Canadell, J. G., Frölicher, T. L., Gasser, T., Houghton, R. A., Le Quéré, C., and Trudinger, C. M.: The declining uptake rate of atmospheric CO₂ by land and ocean sinks, *Biogeosciences*, 11, 3453–3475, <https://doi.org/10.5194/bg-11-3453-2014>, 2014.

Reese, R., Garbe, J., Hill, E. A., Urruty, B., Naughten, K. A., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson,

- 1270 [G. H., Chandler, D., Langebroek, P. M., and Winkelmann, R.: The stability of present-day Antarctic grounding lines – Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded, *The Cryosphere*, 17, 3761–3783, <https://doi.org/10.5194/tc-17-3761-2023>, 2023.](#)
- [Reisinger, A., Fuglestedt, J. S., Pirani, A., Geden, O., Jones, C. D., Maharaj, S., Poloczanska, E. S., Morelli, A., Johansen, T. G., Adler, C., Betts, R. A., and Seneviratne, S. I.: Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5°C, *Annual Review of Environment and Resources*, 50, 185–217, <https://doi.org/10.1146/annurev-environ-111523-102029>, 2025.](#)
- 1275 [Ritchie, P. D. L., Smith, G. S., Davis, K. J., Fezzi, C., Halleck-Vega, S., Harper, A. B., Boulton, C. A., Binner, A. R., Day, B. H., Gallego-Sala, A. V., Mecking, J. V., Sitch, S. A., Lenton, T. M., and Bateman, I. J.: Shifts in national land use and food production in Great Britain after a climate tipping point, *Nat Food*, 1, 76–83, <https://doi.org/10.1038/s43016-019-0011-3>, 2020.](#)
- 1280 [Ritchie, P. D. L., Clarke, J. J., Cox, P. M., and Huntingford, C.: Overshooting tipping point thresholds in a changing climate, *Nature*, 592, 517–523, <https://doi.org/10.1038/s41586-021-03263-2>, 2021.](#)
- [Ritchie, P. D. L., Alkhayyon, H., Cox, P. M., and Wieczorek, S.: Rate-induced tipping in natural and human systems, *Earth Syst. Dynam.*, 14, 669–683, <https://doi.org/10.5194/esd-14-669-2023>, 2023.](#)
- [Ritchie, P. D. L., Huntingford, C., and Cox, P.: ESD Ideas: Climate tipping is not instantaneous – the duration of an overshoot matters, <https://doi.org/10.5194/egusphere-2024-3023>, 15 October 2024.](#)
- 1285 [Robinson, A., Calov, R., and Ganopolski, A.: Multistability and critical thresholds of the Greenland ice sheet, *Nature Clim Change*, 2, 429–432, <https://doi.org/10.1038/nclimate1449>, 2012.](#)
- [Robson, J., Menary, M. B., Sutton, R. T., Mecking, J., Gregory, J. M., Jones, C., Sinha, B., Stevens, D. P., and Wilcox, L. J.: The Role of Anthropogenic Aerosol Forcing in the 1850–1985 Strengthening of the AMOC in CMIP6 Historical Simulations, *Journal of Climate*, 35, 3243–3263, <https://doi.org/10.1175/jcli-d-22-0124.1>, 2022.](#)
- 1290 [Romanou, A., Rind, D., Jonas, J., Miller, R., Kelley, M., Russell, G., Orbe, C., Nazarenko, L., Latto, R., and Schmidt, G. A.: Stochastic Bifurcation of the North Atlantic Circulation under a Midrange Future Climate Scenario with the NASA-GISS ModelE, *Journal of Climate*, 36, 6141–6161, <https://doi.org/10.1175/jcli-d-22-0536.1>, 2023.](#)
- [Romanou, A., Hegerl, G. C., Seneviratne, S. I., Abis, B., Bastos, A., Conversi, A., Landolfi, A., Kim, H., Lerner, P. E., Mekus, J., Otto-Bliesner, B. L., Pausata, F. S. R., Pinto, I., and Suarez-Gutierrez, L.: Extreme Events Contributing to Tipping Elements and Tipping Points, *Surv Geophys*, 46, 375–420, <https://doi.org/10.1007/s10712-024-09863-7>, 2025.](#)
- 1295 [Rooth, C.: Hydrology and ocean circulation, *Progress in Oceanography*, 11, 131–149, \[https://doi.org/10.1016/0079-6611\\(82\\)90006-4\]\(https://doi.org/10.1016/0079-6611\(82\)90006-4\), 1982.](#)
- [Rugenstein, M., Bloch-Johnson, J., Gregory, J., Andrews, T., Mauritsen, T., Li, C., Frölicher, T. L., Paynter, D., Danabasoglu, G., Yang, S., Dufresne, J., Cao, L., Schmidt, G. A., Abe-Ouchi, A., Geoffroy, O., and Knutti, R.: Equilibrium Climate Sensitivity Estimated by Equilibrating Climate Models, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2019gl083898>, 2020.](#)
- 1300 [Sanderson, B. M., Brovkin, V., Fisher, R., Hohn, D., Ilyina, T., Jones, C., Koenigk, T., Koven, C., Li, H., Lawrence, D.,](#)

1305 [Lawrence, P., Liddicoat, S., Macdougall, A., Mengis, N., Nicholls, Z., O'Rourke, E., Romanou, A., Sandstad, M., Schwinger, J., Seferian, R., Sentman, L., Simpson, I., Smith, C., Steinert, N., Swann, A., Tjiputra, J., and Ziehn, T.: flat10MIP: An emissions-driven experiment to diagnose the climate response to positive, zero, and negative CO₂ emissions, <https://doi.org/10.5194/egusphere-2024-3356>, 15 November 2024.](#)

[Santana-Falcón, Y., Yamamoto, A., Lenton, A., Jones, C. D., Burger, F. A., John, J. G., Tjiputra, J., Schwinger, J., Kawamiya, M., Frölicher, T. L., Ziehn, T., and Séférian, R.: Irreversible loss in marine ecosystem habitability after a temperature overshoot, *Commun Earth Environ*, 4, <https://doi.org/10.1038/s43247-023-01002-1>, 2023.](#)

1310 [Scheffer, M., Carpenter, S. R., Dakos, V., and Van Nes, E. H.: Generic Indicators of Ecological Resilience: Inferring the Chance of a Critical Transition, *Annu. Rev. Ecol. Evol. Syst.*, 46, 145–167, <https://doi.org/10.1146/annurev-ecolsys-112414-054242>, 2015.](#)

[Schleussner, C.-F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., Ciais, P., Frölicher, T. L., Fuss, S., Gasser, T., Gidden, M. J., Kropf, C. M., Lacroix, F., Lamboll, R., Martyr, R., Maussion, F., McCaughey, J. W., Meinshausen, M., Mengel, M., Nicholls, Z., Quilcaille, Y., Sanderson, B., Seneviratne, S. I., Sillmann, J., Smith, C. J., Steinert, N. J., Theokritoff, E., Warren, R., Price, J., and Rogelj, J.: Overconfidence in climate overshoot, *Nature*, 634, 366–373, <https://doi.org/10.1038/s41586-024-08020-9>, 2024.](#)

[Schwinger, J. and Tjiputra, J.: Ocean Carbon Cycle Feedbacks Under Negative Emissions, *Geophysical Research Letters*, 45, 5062–5070, <https://doi.org/10.1029/2018gl077790>, 2018.](#)

1320 [Sgubin, G., Swingedouw, D., Drijfhout, S., Mary, Y., and Bennabi, A.: Abrupt cooling over the North Atlantic in modern climate models, *Nat Commun*, 8, <https://doi.org/10.1038/ncomms14375>, 2017.](#)

[Sgubin, G., Swingedouw, D., García De Cortázar-Atauri, I., Ollat, N., and Van Leeuwen, C.: The Impact of Possible Decadal-Scale Cold Waves on Viticulture over Europe in a Context of Global Warming, *Agronomy*, 9, 397, <https://doi.org/10.3390/agronomy9070397>, 2019.](#)

1325 [Silvy, Y., Frölicher, T. L., Terhaar, J., Joos, F., Burger, F. A., Lacroix, F., Allen, M., Bernardello, R., Bopp, L., Brovkin, V., Buzan, J. R., Cadule, P., Dix, M., Dunne, J., Friedlingstein, P., Georgievski, G., Hajima, T., Jenkins, S., Kawamiya, M., Kiang, N. Y., Lapin, V., Lee, D., Lerner, P., Mengis, N., Monteiro, E. A., Paynter, D., Peters, G. P., Romanou, A., Schwinger, J., Sparrow, S., Stofferahn, E., Tjiputra, J., Tourigny, E., and Ziehn, T.: AERA-MIP: emission pathways, remaining budgets, and carbon cycle dynamics compatible with 1.5 and 2 °C global warming stabilization, *Earth Syst. Dynam.*, 15, 1591–1628, <https://doi.org/10.5194/esd-15-1591-2024>, 2024.](#)

[Smith, C. J. and Forster, P. M.: Suppressed Late-20th Century Warming in CMIP6 Models Explained by Forcing and Feedbacks, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2021gl094948>, 2021.](#)

1330 [Solomon, S.: The discovery of the Antarctic ozone hole, *Nature*, 575, 46–47, <https://doi.org/10.1038/d41586-019-02837-5>, 2019.](#)

1335 [Soultan, A., Pavón-Jordán, D., Bradter, U., Sandercock, B. K., Hochachka, W. M., Johnston, A., Brommer, J., Gaget, E., Keller, V., Knaus, P., Aghababayan, K., Maxhuni, Q., Vintchevski, A., Nagy, K., Raudonikis, L., Balmer, D., Noble, D., Leitão,](#)

- D., Oien, I. J., Shimmings, P., Sultanov, E., Caffrey, B., Boyla, K., Radišić, D., Lindström, Å., Veleviski, M., Pladevall, C., Brotons, L., Karel, Š., Rajković, D. Z., Chodkiewicz, T., Wilk, T., Szép, T., Van Turnhout, C., Foppen, R., Burfield, I., Vikström, T., Mazal, V. D., Eaton, M., Vorisek, P., Lehtikainen, A., Herrando, S., Kuzmenko, T., Bauer, H.-G., Kalyakin, M. V., Voltzit, O. V., Sjeničić, J., and Pärt, T.: The future distribution of wetland birds breeding in Europe validated against observed changes in distribution, *Environ. Res. Lett.*, 17, 024025, <https://doi.org/10.1088/1748-9326/ac4e4e>, 2022.
- Staal, A., Fetzner, I., Wang-Erlandsson, L., Bosmans, J. H. C., Dekker, S. C., Van Nes, E. H., Rockström, J., and Tuinenburg, O. A.: Hysteresis of tropical forests in the 21st century, *Nat Commun*, 11, <https://doi.org/10.1038/s41467-020-18728-7>, 2020.
- Stocker, T. F. and Schmittner, A.: Influence of CO₂ emission rates on the stability of the thermohaline circulation, *Nature*, 388, 862–865, <https://doi.org/10.1038/42224>, 1997.
- Stommel, H.: Thermohaline Convection with Two Stable Regimes of Flow, *Tellus*, 13, 224–230, <https://doi.org/10.1111/j.2153-3490.1961.tb00079.x>, 1961.
- Swaminathan, R., Parker, R. J., Jones, C. G., Allan, R. P., Quaife, T., Kelley, D. L., Mora, L. de, and Walton, J.: The Physical Climate at Global Warming Thresholds as Seen in the U.K. Earth System Model, *Journal of Climate*, 35, 29–48, <https://doi.org/10.1175/JCLI-D-21-0234.1>, 2022.
- Swingedouw, D., Braconnot, P., Delecluse, P., Guilyardi, E., and Marti, O.: Quantifying the AMOC feedbacks during a 2×CO₂ stabilization experiment with land-ice melting, *Clim Dyn*, 29, 521–534, <https://doi.org/10.1007/s00382-007-0250-0>, 2007.
- Swingedouw, D., Ifejika Speranza, C., Bartsch, A., Durand, G., Jamet, C., Beaugrand, G., and Conversi, A.: Early Warning from Space for a Few Key Tipping Points in Physical, Biological, and Social-Ecological Systems, *Surv Geophys*, 41, 1237–1284, <https://doi.org/10.1007/s10712-020-09604-6>, 2020.
- Swingedouw, D., Bily, A., Esquerdo, C., Borchert, L. F., Sgubin, G., Mignot, J., and Menary, M.: On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models, *Annals of the New York Academy of Sciences*, 1504, 187–201, <https://doi.org/10.1111/nyas.14659>, 2021.
- Tamarin-Brodsky, T., Hodges, K., Hoskins, B. J., and Shepherd, T. G.: Changes in Northern Hemisphere temperature variability shaped by regional warming patterns, *Nat. Geosci.*, 13, 414–421, <https://doi.org/10.1038/s41561-020-0576-3>, 2020.
- Taylor, P. C., Boeke, R. C., Boisvert, L. N., Feldl, N., Henry, M., Huang, Y., Langen, P. L., Liu, W., Pithan, F., Sejas, S. A., and Tan, I.: Process Drivers, Inter-Model Spread, and the Path Forward: A Review of Amplified Arctic Warming, *Front. Earth Sci.*, 9, <https://doi.org/10.3389/feart.2021.758361>, 2022.
- Tebaldi, C., Ranasinghe, R., Voutsoukas, M., Rasmussen, D. J., Vega-Westhoff, B., Kirezci, E., Kopp, R. E., Sriver, R., and Mentaschi, L.: Extreme sea levels at different global warming levels, *Nat. Clim. Chang.*, 11, 746–751, <https://doi.org/10.1038/s41558-021-01127-1>, 2021.
- Terhaar, J., Frölicher, T. L., Aschwanden, M. T., Friedlingstein, P., and Joos, F.: Adaptive emission reduction approach to reach any global warming target, *Nat. Clim. Chang.*, 12, 1136–1142, <https://doi.org/10.1038/s41558-022-01537-9>, 2022.
- Tokarska, K. B. and Zickfeld, K.: The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change, *Environ. Res. Lett.*, 10, 094013, <https://doi.org/10.1088/1748-9326/10/9/094013>, 2015.

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K., and McGuire, A. D.: Carbon release through abrupt permafrost thaw, *Nat. Geosci.*, 13, 138–143, <https://doi.org/10.1038/s41561-019-0526-0>, 2020.

1375 University of Potsdam and Rahmstorf, S.: Is the Atlantic Overturning Circulation Approaching a Tipping Point?, *Oceanog.*, <https://doi.org/10.5670/oceanog.2024.501>, 2024.

Ureta, C., Ramírez-Barahona, S., Calderón-Bustamante, Ó., Cruz-Santiago, P., Gay-García, C., Swingedouw, D., Defrance, D., and Cuervo-Robayo, A. P.: Evaluation of animal and plant diversity suggests Greenland’s thaw hastens the biodiversity crisis, *Commun Biol.*, 5, <https://doi.org/10.1038/s42003-022-03943-3>, 2022.

1380 Vaittinada Ayar, P., Bopp, L., Christian, J. R., Ilyina, T., Krasting, J. P., Séférian, R., Tsujino, H., Watanabe, M., Yool, A., and Tjiputra, J.: Contrasting projections of the ENSO-driven CO₂ flux variability in the equatorial Pacific under high-warming scenario, *Earth Syst. Dynam.*, 13, 1097–1118, <https://doi.org/10.5194/esd-13-1097-2022>, 2022.

Valdes, P.: Built for stability, *Nature Geosci.*, 4, 414–416, <https://doi.org/10.1038/ngeo1200>, 2011.

Van Breedam, J., Goelzer, H., and Huybrechts, P.: Semi-equilibrated global sea-level change projections for the next 10 000 years, *Earth Syst. Dynam.*, 11, 953–976, <https://doi.org/10.5194/esd-11-953-2020>, 2020.

1385 Van Nes, E. H., Arani, B. M. S., Staal, A., Van Der Bolt, B., Flores, B. M., Bathiany, S., and Scheffer, M.: What Do You Mean, ‘Tipping Point’?, *Trends in Ecology & Evolution*, 31, 902–904, <https://doi.org/10.1016/j.tree.2016.09.011>, 2016.

Van Vuuren, D., O’Neill, B., Tebaldi, C., Chini, L., Friedlingstein, P., Hasegawa, T., Riahi, K., Sanderson, B., Govindasamy, B., Bauer, N., Eyring, V., Fall, C., Frieler, K., Gidden, M., Gohar, L., Jones, A., King, A., Knutti, R., Kriegler, E., Lawrence, P., Lennard, C., Lowe, J., Mathison, C., Mehmood, S., Prado, L., Zhang, Q., Rose, S., Ruane, A., Schleussner, C.-F., Seferian, R., Sillmann, J., Smith, C., Sörensson, A., Panickal, S., Tachiiri, K., Vaughan, N., Vishwanathan, S., Yokohata, T., and Ziehn, T.: The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7), <https://doi.org/10.5194/egusphere-2024-3765>, 30 January 2025.

1390 Van Westen, R. M., Kliphuis, M., and Dijkstra, H. A.: Physics-based early warning signal shows that AMOC is on tipping course, *Sci. Adv.*, 10, <https://doi.org/10.1126/sciadv.adk1189>, 2024.

1395 Vasilakopoulos, P., Raitos, D. E., Tzanatos, E., and Maravelias, C. D.: Resilience and regime shifts in a marine biodiversity hotspot, *Sci Rep.*, 7, <https://doi.org/10.1038/s41598-017-13852-9>, 2017.

WCRP Registered MIPs: <https://wcrp-cmip.org/mips/#registered-mips>, last access: 9 February 2026.

Wehrli, K., Luo, F., Hauser, M., Shiogama, H., Tokuda, D., Kim, H., Coumou, D., May, W., Le Sager, P., Selten, F., Martius, O., Vautard, R., and Seneviratne, S. I.: The ExtremeX global climate model experiment: investigating thermodynamic and dynamic processes contributing to weather and climate extremes, *Earth Syst. Dynam.*, 13, 1167–1196, <https://doi.org/10.5194/esd-13-1167-2022>.

1400 Wei, M., Li, S., Zhu, L., Lu, X., Li, H., and Feng, J.: Continuous Abrupt Vegetation Shifts in the Global Terrestrial Ecosystem, *Ecology Letters*, 28, <https://doi.org/10.1111/ele.70069>, 2025.

1405 Weijer, W., Cheng, W., Garuba, O. A., Hu, A., and Nadiga, B. T.: CMIP6 Models Predict Significant 21st Century Decline of

[the Atlantic Meridional Overturning Circulation, Geophysical Research Letters, 47, https://doi.org/10.1029/2019gl086075, 2020.](https://doi.org/10.1029/2019gl086075)

[van Westen, R. M., Vanderborght, E. Y. P., Kliphuis, M., and Dijkstra, H. A.: Substantial Risk of 21st Century AMOC Tipping even under Moderate Climate Change, https://doi.org/10.48550/ARXIV.2407.19909, 2024.](https://doi.org/10.48550/ARXIV.2407.19909)

1410 [Wilcox, L. J., Allen, R. J., Samset, B. H., Bollasina, M. A., Griffiths, P. T., Keeble, J., Lund, M. T., Makkonen, R., Merikanto, J., O'Donnell, D., Paynter, D. J., Persad, G. G., Rumbold, S. T., Takemura, T., Tsigaridis, K., Undorf, S., and Westervelt, D. M.: The Regional Aerosol Model Intercomparison Project \(RAMIP\), Geosci. Model Dev., 16, 4451–4479, https://doi.org/10.5194/gmd-16-4451-2023, 2023.](https://doi.org/10.5194/gmd-16-4451-2023)

[Williams, A. S. and Igel, A. L.: Cloud Top Radiative Cooling Rate Drives Non-Precipitating Stratiform Cloud Responses to Aerosol Concentration, Geophysical Research Letters, 48, https://doi.org/10.1029/2021gl094740, 2021.](https://doi.org/10.1029/2021gl094740)

1415 [Williams, R. G., Ceppi, P., and Katavouta, A.: Controls of the transient climate response to emissions by physical feedbacks, heat uptake and carbon cycling, Environ. Res. Lett., 15, 0940c1, https://doi.org/10.1088/1748-9326/ab97c9, 2020.](https://doi.org/10.1088/1748-9326/ab97c9)

[Williams, R. G., Goodwin, P., Ceppi, P., Jones, C. D., and MacDougall, A.: A normalised framework for the Zero Emissions Commitment, https://doi.org/10.5194/egusphere-2025-800, 28 March 2025.](https://doi.org/10.5194/egusphere-2025-800)

1420 [Winkelmann, R., Dennis, D. P., Donges, J. F., Loriani, S., Klose, A. K., Abrams, J. F., Alvarez-Solas, J., Albrecht, T., Armstrong McKay, D., Bathiany, S., Blasco Navarro, J., Brovkin, V., Burke, E., Danabasoglu, G., Donner, R. V., Drüke, M., Georgievski, G., Goelzer, H., Harper, A. B., Hegerl, G., Hirota, M., Hu, A., Jackson, L. C., Jones, C., Kim, H., Koenigk, T., Lawrence, P., Lenton, T. M., Liddy, H., Licón-Saláiz, J., Menthon, M., Montoya, M., Nitzbon, J., Nowicki, S., Otto-Bliesner, B., Pausata, F., Rahmstorf, S., Ramin, K., Robinson, A., Rockström, J., Romanou, A., Sakschewski, B., Schädel, C., Sherwood, S., Smith, R. S., Steinert, N. J., Swingedouw, D., Willeit, M., Weijer, W., Wood, R., Wyser, K., and Yang, S.: The Tipping Points Modelling Intercomparison Project \(TIPMIP\): Assessing tipping point risks in the Earth system, https://doi.org/10.5194/egusphere-2025-1899, 18 June 2025.](https://doi.org/10.5194/egusphere-2025-1899)

1425 [Wunderling, N., Staal, A., Sakschewski, B., Hirota, M., Tuinenburg, O. A., Donges, J. F., Barbosa, H. M. J., and Winkelmann, R.: Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest, Proc. Natl. Acad. Sci. U.S.A., 119, https://doi.org/10.1073/pnas.2120777119, 2022.](https://doi.org/10.1073/pnas.2120777119)

1430 [Wunderling, N., Von Der Heydt, A. S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., Brunetti, M., Couplet, V., Kleinen, T., Lear, C. H., Lohmann, J., Roman-Cuesta, R. M., Sinet, S., Swingedouw, D., Winkelmann, R., Anand, P., Barichivich, J., Bathiany, S., Baudena, M., Bruun, J. T., Chiessi, C. M., Coxall, H. K., Docquier, D., Donges, J. F., Falkena, S. K. J., Klose, A. K., Obura, D., Rocha, J., Rynders, S., Steinert, N. J., and Willeit, M.: Climate tipping point interactions and cascades: a review, Earth Syst. Dynam., 15, 41–74, https://doi.org/10.5194/esd-15-41-2024, 2024.](https://doi.org/10.5194/esd-15-41-2024)

1435 [Zickfeld, K. and Herrington, T.: The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission, Environ. Res. Lett., 10, 031001, https://doi.org/10.1088/1748-9326/10/3/031001, 2015.](https://doi.org/10.1088/1748-9326/10/3/031001)

[Zickfeld, K., Azevedo, D., Mathesius, S., and Matthews, H. D.: Asymmetry in the climate–carbon cycle response to positive and negative CO₂ emissions, Nat. Clim. Chang., 11, 613–617, https://doi.org/10.1038/s41558-021-01061-2, 2021.](https://doi.org/10.1038/s41558-021-01061-2)

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N.: Warming caused by cumulative carbon emissions towards the trillionth tonne, *Nature*, 458, 1163–1166, <https://doi.org/10.1038/nature08019>, 2009.

Allen, M. R., Friedlingstein, P., Girardin, C. A. J., Jenkins, S., Malhi, Y., Mitchell-Larson, E., Peters, G. P., and Rajamani, L.: Net Zero: Science, Origins, and Implications, *Annu. Rev. Environ. Resour.*, 47, 849–887, <https://doi.org/10.1146/annurev-environ-112320-105050>, 2022.

Andrews, T., Andrews, M. B., Bodas-Salcedo, A., Jones, G. S., Kuhlbrodt, T., Manners, J., Menary, M. B., Ridley, J., Ringer, M. A., Sellar, A. A., Senior, C. A., and Tang, Y.: Forcings, Feedbacks, and Climate Sensitivity in HadGEM3-GC3.1 and UKESM1, *J. Adv. Model. Earth Syst.*, 11, 4377–4394, <https://doi.org/10.1029/2019ms001866>, 2019.

Andrews, T., Bodas-Salcedo, A., Gregory, J. M., Dong, Y., Armour, K. C., Paynter, D., Lin, P., Modak, A., Mauritsen, T., Cole, J. N. S., Medeiros, B., Benedict, J. J., Douville, H., Roehrig, R., Koshiro, T., Kawai, H., Ogura, T., Dufresne, J., Allan, R. P., and Liu, C.: On the Effect of Historical SST Patterns on Radiative Feedback, *JGR Atmospheres*, 127, <https://doi.org/10.1029/2022jd036675>, 2022.

Armour, K. C., Marshall, J., Scott, J. R., Donohoe, A., and Newsom, E. R.: Southern Ocean warming delayed by circumpolar upwelling and equatorward transport, *Nature Geosci.*, 9, 549–554, <https://doi.org/10.1038/ngeo2731>, 2016.

Armstrong-McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Saksechewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., and Lenton, T. M.: Exceeding 1.5°C global warming could trigger multiple climate tipping points, *Science*, 377, <https://doi.org/10.1126/science.abn7950>, 2022.

Arora, V. K., Katavouta, A., Williams, R. G., Jones, C. D., Brovkin, V., Friedlingstein, P., Schwinger, J., Bopp, L., Boucher, O., Cadule, P., Chamberlain, M. A., Christian, J. R., Delire, C., Fisher, R. A., Hajima, T., Ilyina, T., Joetzier, E., Kawamiya, M., Koven, C. D., Krasting, J. P., Law, R. M., Lawrence, D. M., Lenton, A., Lindsay, K., Pongratz, J., Raddatz, T., Séférian, R., Tachiiri, K., Tjiputra, J. F., Wiltshire, A., Wu, T., and Ziehn, T.: Carbon concentration and carbon-climate feedbacks in CMIP6 models and their comparison to CMIP5 models, *Biogeosciences*, 17, 4173–4222, <https://doi.org/10.5194/bg-17-4173-2020>, 2020.

Asaadi, A., Schwinger, J., Lee, H., Tjiputra, J., Arora, V., Séférian, R., Liddicoat, S., Hajima, T., Santana-Falcón, Y., and Jones, C. D.: Carbon cycle feedbacks in an idealized simulation and a scenario simulation of negative emissions in CMIP6 Earth system models, *Biogeosciences*, 21, 411–435, <https://doi.org/10.5194/bg-21-411-2024>, 2024.

Ben-Yami, M., Good, P., Jackson, L. C., Crucifix, M., Hu, A., Saenko, O., Swingedouw, D., and Boers, N.: Impacts of AMOC Collapse on Monsoon Rainfall: A Multi-Model Comparison, *Earth's Future*, 12, <https://doi.org/10.1029/2023ef003959>, 2024.

Bertini, L. and Tjiputra, J.: Biogeochemical Timescales of Climate Change Onset and Recovery in the North Atlantic Interior Under Rapid Atmospheric CO₂ Forcing, *JGR Oceans*, 127, <https://doi.org/10.1029/2021jc017929>, 2022.

Boehow, N. and Boers, N.: The South American monsoon approaches a critical transition in response to deforestation, *Sci. Adv.*, 9, <https://doi.org/10.1126/sciadv.add9973>, 2023.

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- Boers, N., Marwan, N., Barbosa, H. M. J., and Kurths, J.: A deforestation-induced tipping point for the South American monsoon system, *Sci Rep*, 7, <https://doi.org/10.1038/srep41489>, 2017.
- 1475 Bonan, D. B., Thompson, A. F., Newsom, E. R., Sun, S., and Rugenstein, M.: Transient and Equilibrium Responses of the Atlantic Overturning Circulation to Warming in Coupled Climate Models: The Role of Temperature and Salinity, *Journal of Climate*, 35, 5173–5193, <https://doi.org/10.1175/jcli-d-21-0912.1>, 2022.
- Booth, B. B. B., Jones, C. D., Collins, M., Totterdell, I. J., Cox, P. M., Sitch, S., Huntingford, C., Betts, R. A., Harris, G. R., and Lloyd, J.: High sensitivity of future global warming to land carbon cycle processes, *Environ. Res. Lett.*, 7, 024002, <https://doi.org/10.1088/1748-9326/7/2/024002>, 2012.
- 1480 Bossert, I.: The TIPMIP Earth system model experiment protocol: phase1- datasets for Figures 2, 3 and 4: v1 (v1), Zenodo [code and dataset], <https://zenodo.org/17055322>, 2025.
- Boulton, C. A., Lenton, T. M., and Boers, N.: Pronounced loss of Amazon rainforest resilience since the early 2000s, *Nat. Clim. Chang.*, 12, 271–278, <https://doi.org/10.1038/s41558-022-01287-8>, 2022.
- 1485 Burke, E. J., Zhang, Y., and Krinner, G.: Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change, *The Cryosphere*, 14, 3155–3174, <https://doi.org/10.5194/te-14-3155-2020>, 2020.
- Bush, E. R., Whytock, R. C., Bahaa-el-din, L., Bourgeois, S., Bunnefeld, N., Cardoso, A. W., Dikangadissi, J. T., Dimbonda, P., Dimoto, E., Edzang Ndong, J., Jeffery, K. J., Lehmann, D., Makaga, L., Momboua, B., Momont, L. R. W., Tutin, C. E. G.,
- 1490 White, L. J. T., Whittaker, A., and Abernethy, K.: Long-term collapse in fruit availability threatens Central African forest megafauna, *Science*, 370, 1219–1222, <https://doi.org/10.1126/science.abc7791>, 2020.
- Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., and Saba, V.: Observed fingerprint of a weakening Atlantic Ocean overturning circulation, *Nature*, 556, 191–196, <https://doi.org/10.1038/s41586-018-0006-5>, 2018.
- Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., and Rahmstorf, S.: Current Atlantic Meridional Overturning Circulation weakest in last millennium, *Nat. Geosci.*, 14, 118–120, <https://doi.org/10.1038/s41561-021-00699-z>, 2021.
- 1495 Cano, I. M., Shevliakova, E., Malyshev, S., John, J. G., Yu, Y., Smith, B., and Pacala, S. W.: Abrupt loss and uncertain recovery from fires of Amazon forests under low climate mitigation scenarios, *Proc. Natl. Acad. Sci. U.S.A.*, 119, <https://doi.org/10.1073/pnas.2203200119>, 2022.
- Cassidy, L. J., King, A. D., Brown, J. R., MacDougall, A. H., Ziehn, T., Min, S. K., and Jones, C. D.: Regional temperature extremes and vulnerability under net zero CO₂ emissions, *Environ. Res. Lett.*, 19, 014051, <https://doi.org/10.1088/1748-9326/ad114a>, 2024.
- 1500 Chamberlain, M. A., Ziehn, T., and Law, R. M.: The Southern Ocean as the climate's freight train—driving ongoing global warming under zero-emission scenarios with ACCESS-ESM1.5, *Biogeosciences*, 21, 3053–3073, <https://doi.org/10.5194/bg-21-3053-2024>, 2024.
- 1505 Chapman, R., Sinet, S., and Ritchie, P. D. L.: Tipping mechanisms in a conceptual model of the Atlantic Meridional Overturning Circulation, *Weather*, 79, 316–323, <https://doi.org/10.1002/wea.7609>, 2024.

Chen, X., and Tung, K.-K.: Global surface warming enhanced by weak Atlantic overturning circulation, *Nature*, 559, 387–391, <https://doi.org/10.1038/s41586-018-0320-y>, 2018.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J.: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model, *Nature*, 408, 184–187, <https://doi.org/10.1038/35041539>, 2000.

Da Cruz, D. C., Benayas, J. M. R., Ferreira, G. C., Santos, S. R., and Schwartz, G.: An overview of forest loss and restoration in the Brazilian Amazon, *New Forests*, 52, 1–16, <https://doi.org/10.1007/s11056-020-09777-3>, 2021.

De Vrese, P. and Brovkin, V.: Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios, *Nat Commun*, 12, <https://doi.org/10.1038/s41467-021-23010-5>, 2021.

Defrance, D., Ramstein, G., Charbit, S., Vrac, M., Farnien, A. M., Sultan, B., Swingedouw, D., Dumas, C., Gemenne, F., Alvarez Solas, J., and Vanderlinden, J. P.: Consequences of rapid ice sheet melting on the Sahelian population vulnerability, *Proc. Natl. Acad. Sci. U.S.A.*, 114, 6533–6538, <https://doi.org/10.1073/pnas.1619358114>, 2017.

DeVries, T., Holzer, M., and Primeau, F.: Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning, *Nature*, 542, 215–218, <https://doi.org/10.1038/nature21068>, 2017.

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingford, C., Scheffer, M., Sgubin, G., and Swingedouw, D.: Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models, *Proc. Natl. Acad. Sci. U.S.A.*, 112, <https://doi.org/10.1073/pnas.1511451112>, 2015.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Sentman, L. T., Aderoft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, R. W., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J., and Zadeh, N.: GFDL's ESM2 Global Coupled Climate Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics*, *Journal of Climate*, 26, 2247–2267, <https://doi.org/10.1175/jcli-d-12-00150.1>, 2013.

Dunne, J. P., Hewitt, H. T., Arblaster, J., Bonou, F., Boucher, O., Cavazos, T., Durack, P. J., Hassler, B., Jukes, M., Miyakawa, T., Mizielinski, M., Naik, V., Nicholls, Z., O'Rourke, E., Pineus, R., Sanderson, B. M., Simpson, I. R., and Taylor, K. E.: An evolving Coupled Model Intercomparison Project phase 7 (CMIP7) and Fast Track in support of future climate assessment, <https://doi.org/10.5194/egusphere-2024-3874>, 20 December 2024.

Evin, G., Ribes, A., and Corre, L.: Assessing CMIP6 uncertainties at global warming levels, *Clim Dyn*, 62, 8057–8072, <https://doi.org/10.1007/s00382-024-07323-x>, 2024.

Feldmann, J. and Levermann, A.: Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin, *Proc. Natl. Acad. Sci. U.S.A.*, 112, 14191–14196, <https://doi.org/10.1073/pnas.1512482112>, 2015.

Fischer, E. M., Sippel, S., and Knutti, R.: Increasing probability of record-shattering climate extremes, *Nat. Clim. Chang.*, 11, 689–695, <https://doi.org/10.1038/s41558-021-01092-9>, 2021.

Flores, B. M., Montoya, E., Sakchewski, B., Nascimento, N., Staal, A., Betts, R. A., Levis, C., Lapola, D. M., Esquivel-Muelbert, A., Jakovac, C., Nobre, C. A., Oliveira, R. S., Borma, L. S., Nian, D., Boers, N., Hecht, S. B., Ter Steege, H., Arieira,

1540 J., Lucas, I. L., Berenguer, E., Marengo, J. A., Gatti, L. V., Mattos, C. R. C., and Hirota, M.: Critical transitions in the Amazon forest system, *Nature*, 626, 555–564, <https://doi.org/10.1038/s41586-023-06970-0>, 2024.

Fons, E., Runge, J., Neubauer, D., and Lohmann, U.: Stratocumulus adjustments to aerosol perturbations disentangled with a causal approach, *npj Clim Atmos Sci*, 6, <https://doi.org/10.1038/s41612-023-00452-w>, 2023.

Franzke, C. L. E., Ciullo, A., Gilmore, E. A., Matias, D. M., Nagabhatla, N., Orlov, A., Paterson, S. K., Scheffran, J., and Sillmann, J.: Perspectives on tipping points in integrated models of the natural and human Earth system: cascading effects and telecoupling, *Environ. Res. Lett.*, 17, 015004, <https://doi.org/10.1088/1748-9326/ac42fd>, 2022.

1545 Fraser, N. J. and Cunningham, S. A.: 120 Years of AMOC Variability Reconstructed From Observations Using the Bernoulli Inverse, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2021gl093893>, 2021.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijckx, I., T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Arneeth, A., Arora, V., Bates, N. R., Becker, M., Bellouin, N., Berghoff, C. F., Bittig, H. C., Bopp, L., Cadule, P., Campbell, K., Chamberlain, M. A., Chandra, N., Chevallier, F., Chini, L. P., Colligan, T., Deaeux, J., Djeutehouang, L. M., Dou, X., Duran-Rojas, C., Enyo, K., Evans, W., Fay, A. R., Feely, R. A., Ford, D. J., Foster, A., Gasser, T., Gehlen, M., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Hurtt, G. C., Iida, Y., Ilyina, T., Jacobson, A. R., Jain, A. K., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Kato, E., Keeling, R. F., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Lan, X., Lauvset, S. K., Lefèvre, N., Liu, Z., Liu, J., Ma, L., Maksyutov, S., Marland, G., Mayot, N., McGuire, P. C., Metzl, N., Monaaci, N. M., Morgan, E. J., Nakaoka, S. I., Neill, C., Niwa, Y., Nützel, T., Olivier, L., Ono, T., Palmer, P. I., Pierrot, D., Qin, Z., Resplandy, L., Roobaert, A., Rosan, T. M., Rödenbeck, C., Schwinger, J., Smallman, T. L., Smith, S. M., Sospedra-Alfonso, R., Steinhoff, T., et al.: Global Carbon Budget 2024, *Earth Syst. Sci. Data*, 17, 965–1039, <https://doi.org/10.5194/essd-17-965-2025>, 2025.

1550 Frieler, K., Volkholz, J., Lange, S., Schewe, J., Mengel, M., Del Río Rivas López, M., Otto, C., Reyer, C. P. O., Karger, D. N., Malle, J. T., Treu, S., Menz, C., Blanchard, J. L., Harrison, C. S., Petrik, C. M., Eddy, T. D., Ortega-Cisneros, K., Novaglio, C., Rousseau, Y., Watson, R. A., Stock, C., Liu, X., Heneghan, R., Tittensor, D., Maury, O., Büchner, M., Vogt, T., Wang, T., Sun, F., Sauer, I. J., Koch, J., Vanderkelen, I., Jägermeyr, J., Müller, C., Rabin, S., Klar, J., Vega Del Valle, I. D., Lasslop, G., Chadburn, S., Burke, E., Gallego-Sala, A., Smith, N., Chang, J., Hantson, S., Burton, C., Gädeke, A., Li, F., Gosling, S. N., Müller-Schmied, H., Hattermann, F., Wang, J., Yao, F., Hickler, T., Mareé, R., Pierson, D., Thiery, W., Mercado-Bettin, D., Ladwig, R., Ayala-Zamora, A. I., Forrest, M., and Bechtold, M.: Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP3a), *Geosci. Model Dev.*, 17, 1–51, <https://doi.org/10.5194/gmd-17-1-2024>, 2024.

1565 Fröb, F., Bourgeois, T., Goris, N., Schwinger, J., and Heinze, C.: Simulated Abrupt Shifts in Aerobic Habitats of Marine Species in the Past, Present, and Future, *Earth's Future*, 12, <https://doi.org/10.1029/2023ef004141>, 2024.

Frölicher, T. L. and Joos, F.: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle climate model, *Clim Dyn*, 35, 1439–1459, <https://doi.org/10.1007/s00382-009-0727-0>, 2010.

Frölicher, T. L. and Paynter, D. J.: Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales, *Environ. Res. Lett.*, 10, 075002, <https://doi.org/10.1088/1748-9326/10/7/075002>, 2015.

Garbe, J., Albrecht, T., Levermann, A., Donges, J. F., and Winkelmann, R.: The hysteresis of the Antarctic Ice Sheet, *Nature*, 585, 538–544, <https://doi.org/10.1038/s41586-020-2727-5>, 2020.

Gerten, D., Lucht, W., Ostberg, S., Heinke, J., Kowarsch, M., Kreft, H., Kundzewicz, Z. W., Rastgooy, J., Warren, R., and Schellnhuber, H. J.: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems, *Environ. Res. Lett.*, 8, 034032, <https://doi.org/10.1088/1748-9326/8/3/034032>, 2013.

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., Van Vuuren, D. P., Van Den Berg, M., Feng, L., Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R., Horing, J., Popp, A., Stehfest, E., and Takahashi, K.: Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, *Geosci. Model Dev.*, 12, 1443–1475, <https://doi.org/10.5194/gmd-12-1443-2019>, 2019.

Gillett, N. P., Arora, V. K., Matthews, D., and Allen, M. R.: Constraining the Ratio of Global Warming to Cumulative CO₂ Emissions Using CMIP5 Simulations*, *Journal of Climate*, 26, 6844–6858, <https://doi.org/10.1175/jcli-d-12-00476.1>, 2013.

Gillett, N. P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G. C., Knutti, R., Gastineau, G., John, J. G., Li, L., Nazarenko, L., Rosenbloom, N., Seland, Ø., Wu, T., Yukimoto, S., and Ziehn, T.: Constraining human contributions to observed warming since the pre-industrial period, *Nat. Clim. Chang.*, 11, 207–212, <https://doi.org/10.1038/s41558-020-00965-9>, 2021.

Gjermundsen, A., Nummelin, A., Olivé, D., Bentsen, M., Seland, Ø., and Schulz, M.: Shutdown of Southern Ocean convection controls long-term greenhouse gas-induced warming, *Nat. Geosci.*, 14, 724–731, <https://doi.org/10.1038/s41561-021-00825-x>, 2021.

Golledge, N. R., Levy, R. H., McKay, R. M., and Naish, T. R.: East Antarctic ice sheet most vulnerable to Weddell Sea warming, *Geophysical Research Letters*, 44, 2343–2351, <https://doi.org/10.1002/2016gl072422>, 2017.

Good, P., Jones, C., Lowe, J., Betts, R., Booth, B., and Huntingford, C.: Quantifying Environmental Drivers of Future Tropical Forest Extent, *Journal of Climate*, 24, 1337–1349, <https://doi.org/10.1175/2010jcli3865.1>, 2011.

Gregory, J. M., George, S. E., and Smith, R. S.: Large and irreversible future decline of the Greenland ice sheet, *The Cryosphere*, 14, 4299–4322, <https://doi.org/10.5194/tc-14-4299-2020>, 2020.

Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döschner, R., Gehlen, M., Gruber, N., Holland, E., Hov, Ø., Joos, F., Matthews, J. B. R., Rodven, R., and Wilson, S.: The quiet crossing of ocean tipping points, *Proc. Natl. Acad. Sci. U.S.A.*, 118, <https://doi.org/10.1073/pnas.2008478118>, 2021.

605 Heinze, C., Blenckner, T., Brown, P., Fröb, F., Morée, A., New, A. L., Nissen, C., Rynders, S., Seguro, I., Aksenov, Y., Artioli, Y., Bourgeois, T., Burger, F., Buzan, J., Cael, B. B., Yumruktepe, V. Ç., Chierici, M., Danek, C., Diekmann, U., Fransson, A., Frölicher, T., Galli, G., Gehlen, M., González, A. G., Gonzalez-Davila, M., Gruber, N., Gustafsson, Ö., Hauck, J., Heino, M., Henson, S., Hieronymus, J., Huertas, I. E., Jebri, F., Jeltsch-Thömmes, A., Joos, F., Joshi, J., Kelly, S., Menon, N., Mongwe, P., Oziel, L., Ólafsdóttir, S., Palmieri, J., Pérez, F. F., Ranith, R. P., Ramanantsoa, J., Roy, T., Rusiecka, D., Santana
 610 Casiano, J. M., Santana-Falcón, Y., Schwinger, J., Séférian, R., Seifert, M., Shchiptsova, A., Sinha, B., Somes, C., Steinfeldt, R., Tao, D., Tjiputra, J., Ulfssbo, A., Völker, C., Wakamatsu, T., and Ye, Y.: Reviews and syntheses: Abrupt ocean biogeochemical change under human-made climatic forcing—warming, acidification, and deoxygenation, <https://doi.org/10.5194/bg-2023-182>, 2023.

Held, I. M., Winton, M., Takahashi, K., Delworth, T., Zeng, F., and Vallis, G. K.: Probing the Fast and Slow Components of
 615 Global Warming by Returning Abruptly to Preindustrial Forcing, *Journal of Climate*, 23, 2418–2427, <https://doi.org/10.1175/2009jcli3466.1>, 2010.

Heuzé, C. and Jahn, A.: The first ice-free day in the Arctic Ocean could occur before 2030, *Nat Commun*, 15, <https://doi.org/10.1038/s41467-024-54508-3>, 2024.

Höning, D., Willeit, M., Calov, R., Klemann, V., Bagge, M., and Ganopolski, A.: Multistability and Transient Response of the
 620 Greenland Ice Sheet to Anthropogenic CO₂ Emissions, *Geophysical Research Letters*, 50, <https://doi.org/10.1029/2022gl1101827>, 2023.

Horton, D. E., Johnson, N. C., Singh, D., Swain, D. L., Rajaratnam, B., and Diffenbaugh, N. S.: Contribution of changes in atmospheric circulation patterns to extreme temperature trends, *Nature*, 522, 465–469, <https://doi.org/10.1038/nature14550>, 2015.

625 Hu, A., Otto-Bliesner, B. L., Meehl, G. A., Han, W., Morrill, C., Brady, E. C., and Briegleb, B.: Response of Thermohaline Circulation to Freshwater Forcing under Present-Day and LGM Conditions, *Journal of Climate*, 21, 2239–2258, <https://doi.org/10.1175/2007jcli1985.1>, 2008.

IPCC: Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, 1st ed.,
 630 Cambridge University Press, <https://doi.org/10.1017/9781009157940>, 2022.

IPCC: The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press, <https://doi.org/10.1017/9781009157964>, 2022.

IPCC: Climate Change 2021—The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st ed., Cambridge University Press,
 635 <https://doi.org/10.1017/9781009157896>, 2023.

IPCC: Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero

(eds.)). IPCC, Geneva, Switzerland, Intergovernmental Panel on Climate Change, <https://doi.org/10.59327/ipcc/ar6-9789291691647.001>, 2023.

1640 Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Meeking, J. V., and Wood, R. A.: Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, *Clim Dyn*, 45, 3299–3316, <https://doi.org/10.1007/s00382-015-2540-2>, 2015.

Jackson, L. C., Alastrué De Asenjo, E., Bellomo, K., Danabasoglu, G., Haak, H., Hu, A., Jungelaus, J., Lee, W., Meccia, V. L., Saenko, O., Shao, A., and Swingedouw, D.: Understanding AMOC stability: the North Atlantic Hosing Model
1645 Interecomparison Project, *Geosci. Model Dev.*, 16, 1975–1995, <https://doi.org/10.5194/gmd-16-1975-2023>, 2023.

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D. E., Coscieme, L., Golden, A. S., Guerra, C. A., Jacob, U., Takahashi, Y., Settele, J., Díaz, S., Molnár, Z., and Purvis, A.: The direct drivers of recent global anthropogenic biodiversity loss, *Sci. Adv.*, 8, <https://doi.org/10.1126/sciadv.abm9982>, 2022.

Jeltsch-Thömmes, A., Stocker, T. F., and Joos, F.: Hysteresis of the Earth system under positive and negative CO₂ emissions, *Environ. Res. Lett.*, 15, 124026, <https://doi.org/10.1088/1748-9326/abe4af>, 2020.

1650 Jensen, L., Gerdener, H., Eicker, A., Kutsche, J., and Fiedler, S.: Observations indicate regionally misleading wetting and drying trends in CMIP6, *npj Clim Atmos Sci*, 7, <https://doi.org/10.1038/s41612-024-00788-x>, 2024.

Jones, C. D. and Friedlingstein, P.: Quantifying process-level uncertainty contributions to TCRE and carbon budgets for meeting Paris Agreement climate targets, *Environmental Research Letters*, 15, 074019, <https://doi.org/10.1088/1748-9326/ab858a>, 2020.

1655 Jones, C. D., Ciais, P., Davis, S. J., Friedlingstein, P., Gasser, T., Peters, G. P., Rogelj, J., Van Vuuren, D. P., Canadell, J. G., Cowie, A., Jackson, R. B., Jonas, M., Kriegler, E., Littleton, E., Lowe, J. A., Milne, J., Shrestha, G., Smith, P., Torvanger, A., and Wiltshire, A.: Simulating the Earth system response to negative emissions, *Environ. Res. Lett.*, 11, 095012, <https://doi.org/10.1088/1748-9326/11/9/095012>, 2016.

1660 Jones, C. D., Frölicher, T. L., Koven, C., MacDougall, A. H., Matthews, H. D., Zickfeld, K., Rogelj, J., Tokarska, K. B., Gillett, N. P., Ilyina, T., Meinshausen, M., Mengis, N., Séférian, R., Eby, M., and Burger, F. A.: The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions, *Geosci. Model Dev.*, 12, 4375–4385, <https://doi.org/10.5194/gmd-12-4375-2019>, 2019.

Keller, D. P., Lenton, A., Scott, V., Vaughan, N. E., Bauer, N., Ji, D., Jones, C. D., Kravitz, B., Muri, H., and Zickfeld, K.:
1665 The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6, *Geosci. Model Dev.*, 11, 1133–1160, <https://doi.org/10.5194/gmd-11-1133-2018>, 2018.

Kilbourne, K. H., Wanamaker, A. D., Moffa Sanchez, P., Reynolds, D. J., Amrhein, D. E., Butler, P. G., Gebbie, G., Goes, M., Jansen, M. F., Little, C. M., Mette, M., Moreno-Chamarro, E., Ortega, P., Otto-Bliesner, B. L., Rossby, T., Seourse, J., and Whitney, N. M.: Atlantic circulation change still uncertain, *Nat. Geosci.*, 15, 165–167, <https://doi.org/10.1038/s41561-022-00896-4>, 2022.

- Kim, S.-K., and An, S.-I.: Emergence of a climate oscillation in the Arctic Ocean due to global warming, *Nat. Clim. Chang.*, 14, 1268–1274, <https://doi.org/10.1038/s41558-024-02171-3>, 2024.
- King, A. D., Lane, T. P., Henley, B. J., and Brown, J. R.: Global and regional impacts differ between transient and equilibrium warmer worlds, *Nat. Clim. Chang.*, 10, 42–47, <https://doi.org/10.1038/s41558-019-0658-7>, 2020.
- 1675 King, A. D., Sniderman, J. M. K., Dittus, A. J., Brown, J. R., Hawkins, E., and Ziehn, T.: Studying climate stabilization at Paris Agreement levels, *Nat. Clim. Chang.*, 11, 1010–1013, <https://doi.org/10.1038/s41558-021-01225-0>, 2021.
- King, A. D., Ziehn, T., Chamberlain, M., Borowiak, A. R., Brown, J. R., Cassidy, L., Dittus, A. J., Grose, M., Maher, N., Paik, S., Perkins-Kirkpatrick, S. E., and Sengupta, A.: Exploring climate stabilisation at different global warming levels in ACCESS-ESM-1.5, *Earth Syst. Dynam.*, 15, 1353–1383, <https://doi.org/10.5194/esd-15-1353-2024>, 2024.
- 1680 Kjellström, E., Nikulin, G., Strandberg, G., Christensen, O. B., Jacob, D., Keuler, K., Lenderink, G., Van Meijgaard, E., Schär, C., Somot, S., Sørland, S. L., Teichmann, C., and Vautard, R.: European climate change at global mean temperature increases of 1.5 and 2 °C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models, *Earth Syst. Dynam.*, 9, 459–478, <https://doi.org/10.5194/esd-9-459-2018>, 2018.
- Klose, A. K., Karle, V., Winkelmann, R., and Donges, J. F.: Emergence of cascading dynamics in interacting tipping elements of ecology and climate, *R. Soc. open sci.*, 7, 200599, <https://doi.org/10.1098/rsos.200599>, 2020.
- 1685 Klose, A. K., Donges, J. F., Feudel, U., and Winkelmann, R.: Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation, *Earth Syst. Dynam.*, 15, 635–652, <https://doi.org/10.5194/esd-15-635-2024>, 2024.
- Koenigk, T., Bärring, L., Matei, D., Nikulin, G., Strandberg, G., Tyrlis, E., Wang, S., and Willeke, R.: On the contribution of internal climate variability to European future climate trends, *Tellus A: Dynamic Meteorology and Oceanography*, 72, 1788901, <https://doi.org/10.1080/16000870.2020.1788901>, 2020.
- 1690 Koven, C. D.: Boreal carbon loss due to poleward shift in low-carbon ecosystems, *Nature Geosci.*, 6, 452–456, <https://doi.org/10.1038/ngeo1801>, 2013.
- Koven, C. D., Arora, V. K., Cadule, P., Fisher, R. A., Jones, C. D., Lawrence, D. M., Lewis, J., Lindsay, K., Mathesius, S., 1695 Meinshausen, M., Mills, M., Nicholls, Z., Sanderson, B. M., Séférian, R., Swart, N. C., Wieder, W. R., and Zickfeld, K.: Multi-century dynamics of the climate and carbon cycle under both high and net-negative emissions scenarios, *Earth Syst. Dynam.*, 13, 885–909, <https://doi.org/10.5194/esd-13-885-2022>, 2022.
- Koven, C. D., Sanderson, B. M., and Swann, A. L. S.: Much of zero-emissions commitment occurs before reaching net-zero emissions, *Environ. Res. Lett.*, 18, 014017, <https://doi.org/10.1088/1748-9326/acab1a>, 2023.
- 1700 Krasting, J. P., Dunne, J. P., Shevliakova, E., and Stouffer, R. J.: Trajectory sensitivity of the transient climate response to cumulative carbon emissions, *Geophys. Res. Lett.*, 41, 2520–2527, <https://doi.org/10.1002/2013gl059141>, 2014.
- Kubelka, V., Sanderecock, B. K., Székely, T., and Freckleton, R. P.: Animal migration to northern latitudes: environmental changes and increasing threats, *Trends in Ecology & Evolution*, 37, 30–41, <https://doi.org/10.1016/j.tree.2021.08.010>, 2022.

- Kug, J. S., Oh, J. H., An, S. I., Yeh, S. W., Min, S. K., Son, S. W., Kam, J., Ham, Y. G., and Shin, J.: Hysteresis of the intertropical convergence zone to CO₂ forcing, *Nat. Clim. Chang.*, 12, 47–53, <https://doi.org/10.1038/s41558-021-01211-6>, 2022.
- Laeroix, F., Burger, F. A., Silvy, Y., Schleussner, C., and Frölicher, T. L.: Persistently Elevated High-Latitude Ocean Temperatures and Global Sea Level Following Temporary Temperature Overshoots, *Earth's Future*, 12, <https://doi.org/10.1029/2024ef004862>, 2024.
- Lennard, C. J., Nikulin, G., Dosio, A., and Moufouma-Okia, W.: On the need for regional climate information over Africa under varying levels of global warming, *Environ. Res. Lett.*, 13, 060401, <https://doi.org/10.1088/1748-9326/aab2b4>, 2018.
- Lenton, T. M.: Arctic Climate Tipping Points, *AMBIO*, 41, 10–22, <https://doi.org/10.1007/s13280-011-0221-x>, 2012.
- Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, *Proc. Natl. Acad. Sci. U.S.A.*, 105, 1786–1793, <https://doi.org/10.1073/pnas.0705414105>, 2008.
- Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., and Schellnhuber, H. J.: Climate tipping points—too risky to bet against, *Nature*, 575, 592–595, <https://doi.org/10.1038/d41586-019-03595-0>, 2019.
- Lenton, T. M., Armstrong-McKay, D. I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., Milkoreit, M., Powell, T., Smith, S. R., Zimm, C., Buxton, J. E., Bailey, E., Laybourn, L., Ghadiali, A., Dyke, J. G. (eds): The Global Tipping Points Report 2023, University of Exeter, Exeter, UK, <https://report-2023-global-tipping-points.org/-2023>.
- Lenton, T. M., Abrams, J. F., Bartsch, A., Bathiany, S., Boulton, C. A., Buxton, J. E., Conversi, A., Cunliffe, A. M., Hebden, S., Laverne, T., Poulter, B., Shepherd, A., Smith, T., Swingedouw, D., Winkelmann, R., and Boers, N.: Remotely sensing potential climate change tipping points across scales, *Nat Commun.*, 15, <https://doi.org/10.1038/s41467-023-44609-w>, 2024.
- Levermann, A. and Winkelmann, R.: A simple equation for the melt elevation feedback of ice sheets, *The Cryosphere*, 10, 1799–1807, <https://doi.org/10.5194/tc-10-1799-2016>, 2016.
- Levermann, A., Clark, P. U., Marzeion, B., Milne, G. A., Pollard, D., Radic, V., and Robinson, A.: The multimillennial sea-level commitment of global warming, *Proc. Natl. Acad. Sci. U.S.A.*, 110, 13745–13750, <https://doi.org/10.1073/pnas.1219414110>, 2013.
- Li, S., Huang, G., Li, X., Liu, J., and Fan, G.: An Assessment of the Antarctic Sea Ice Mass Budget Simulation in CMIP6 Historical Experiment, *Front. Earth Sci.*, 9, <https://doi.org/10.3389/feart.2021.649743>, 2021.
- Lieon-Salaiz, J., tipmip-methods/tipmip-data-req: v1.1.1 (v1.1.1). Zenodo. <https://doi.org/10.5281/zenodo.15189530>, 2025.
- Litzow, M. A. and Hunsicker, M. E.: Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems, *Ecosphere*, 7, <https://doi.org/10.1002/ecs2.1614>, 2016.
- Liu, W., Fedorov, A. V., Xie, S. P., and Hu, S.: Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate, *Sci. Adv.*, 6, <https://doi.org/10.1126/sciadv.aaz4876>, 2020.
- Liu-Helmersson, J., Stenlund, H., Wilder-Smith, A., and Rocklöv, J.: Vectorial Capacity of *Aedes aegypti*: Effects of Temperature and Implications for Global Dengue Epidemic Potential, *PLoS ONE*, 9, e89783, <https://doi.org/10.1371/journal.pone.0089783>, 2014.

Lovejoy, T. E. and Nobre, C.: Amazon Tipping Point, *Sci. Adv.*, 4, <https://doi.org/10.1126/sciadv.aat2340>, 2018.

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra, J., Wiltshire, A., and Ziehn, T.: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO₂, *Biogeosciences*, 17, 2987–3016, <https://doi.org/10.5194/bg-17-2987-2020>, 2020.

McCarthy, G. D. and Caesar, L.: Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past?, *Phil. Trans. R. Soc. A*, 381, <https://doi.org/10.1098/rsta.2022.0193>, 2023.

Mecking, J. V., Drijfhout, S. S., Jackson, L. C., and Andrews, M. B.: The effect of model bias on Atlantic freshwater transport and implications for AMOC bi-stability, *Tellus A: Dynamic Meteorology and Oceanography*, 69, 1299910, <https://doi.org/10.1080/16000870.2017.1299910>, 2017.

Menary, M. B., Robson, J., Allan, R. P., Booth, B. B.-B., Cassou, C., Gastineau, G., Gregory, J., Hodson, D., Jones, C., Mignot, J., Ringer, M., Sutton, R., Wilcox, L., and Zhang, R.: Aerosol-Forced AMOC Changes in CMIP6 Historical Simulations, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2020gl088166>, 2020.

Morée, A. L., Lae-roix, F., Cheung, W. W. L., and Frölicher, T. L.: Long-term impacts of global temperature stabilization and overshoot on exploited marine species, *Biogeosciences*, 22, 1115–1133, <https://doi.org/10.5194/bg-22-1115-2025>, 2025.

Mykssvoll, M. S., Britt Sando, A., Tjiputra, J., Samuelsen, A., Çağlar Yumruketepe, V., Li, C., Mousing, E. A., Bettencourt, J. P. H., and Ottersen, G.: Key physical processes and their model representation for projecting climate impacts on subarctic Atlantic net primary production: A synthesis, *Progress in Oceanography*, 217, 103084, <https://doi.org/10.1016/j.pocean.2023.103084>, 2023.

Natali, S. M., Holdren, J. P., Rogers, B. M., Treharne, R., Duffy, P. B., Pomerance, R., and MacDonald, E.: Permafrost carbon feedbacks threaten global climate goals, *Proc. Natl. Acad. Sci. U.S.A.*, 118, <https://doi.org/10.1073/pnas.2100163118>, 2021.

Naughten, K. A., Holland, P. R., and De Rydt, J.: Unavoidable future increase in West Antarctic ice shelf melting over the twenty-first century, *Nat. Clim. Chang.*, 13, 1222–1228, <https://doi.org/10.1038/s41558-023-01818-x>, 2023.

Nian, D., Bathiany, S., Ben-Yami, M., Blaschke, L. L., Hirota, M., Rodrigues, R. R., and Boers, N.: A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests, *Commun. Earth Environ.*, 4, <https://doi.org/10.1038/s43247-023-01123-7>, 2023.

Nitzbon, J., Schneider Von Deimling, T., Aliyeva, M., Chadburn, S. E., Grosse, G., Laboor, S., Lee, H., Lohmann, G., Steinert, N. J., Stuenzi, S. M., Werner, M., Westermann, S., and Langer, M.: No respite from permafrost thaw impacts in the absence of a global tipping point, *Nat. Clim. Chang.*, 14, 573–585, <https://doi.org/10.1038/s41558-024-02011-4>, 2024.

Noël, B., Van Kampenhout, L., Lenaerts, J. T. M., Van De Berg, W. J., and Van Den Broeke, M. R.: A 21st Century Warming Threshold for Sustained Greenland Ice Sheet Mass Loss, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2020gl090471>, 2021.

Notz, D., and Community, S.: Arctic Sea Ice in CMIP6, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2019gl086749>, 2020.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, *Geosci. Model Dev.*, 9, 3461–3482, <https://doi.org/10.5194/gmd-9-3461-2016>, 2016.

Parry, I. M., Ritchie, P. D. L., and Cox, P. M.: Evidence of localised Amazon rainforest dieback in CMIP6 models, *Earth Syst. Dynam.*, 13, 1667–1675, <https://doi.org/10.5194/esd-13-1667-2022>, 2022.

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., Kuipers Munneke, P., Lenaerts, J. T. M., Nowicki, S., Payne, A. J., Robinson, A., Seroussi, H., Trusel, L. D., and Van Den Broeke, M.: The Greenland and Antarctic ice sheets under 1.5 °C global warming, *Nature Clim. Change*, 8, 1053–1061, <https://doi.org/10.1038/s41558-018-0305-8>, 2018.

Portmann, V., Chavent, M., and Swingedouw, D.: CLimLoco1.0: CLimate variable confidence Interval of Multivariate Linear Observational CONstraint, <https://doi.org/10.5194/egusphere-2025-62>, 24 January 2025.

Randerson, J. T., Lindsay, K., Munoz, E., Fu, W., Moore, J. K., Hoffman, F. M., Mahowald, N. M., and Doney, S. C.: Multicentury changes in ocean and land contributions to the climate-carbon feedback, *Global Biogeochemical Cycles*, 29, 744–759, <https://doi.org/10.1002/2014gb005079>, 2015.

Raupach, M. R., Gloor, M., Sarmiento, J. L., Canadell, J. G., Frölicher, T. L., Gasser, T., Houghton, R. A., Le Quéré, C., and Trudinger, C. M.: The declining uptake rate of atmospheric CO₂ by land and ocean sinks, *Biogeosciences*, 11, 3453–3475, <https://doi.org/10.5194/bg-11-3453-2014>, 2014.

Reese, R., Garbe, J., Hill, E. A., Urruty, B., Naughten, K. A., Gagliardini, O., Durand, G., Gillet-Chaulet, F., Gudmundsson, G. H., Chandler, D., Langebroek, P. M., and Winkelmann, R.: The stability of present-day Antarctic grounding lines — Part 2: Onset of irreversible retreat of Amundsen Sea glaciers under current climate on centennial timescales cannot be excluded, *The Cryosphere*, 17, 3761–3783, <https://doi.org/10.5194/te-17-3761-2023>, 2023.

Ritchie, P. D. L., Smith, G. S., Davis, K. J., Fezzi, C., Halleck-Vega, S., Harper, A. B., Boulton, C. A., Binner, A. R., Day, B. H., Gallego-Sala, A. V., Mecking, J. V., Stich, S. A., Lenton, T. M., and Bateman, I. J.: Shifts in national land-use and food production in Great Britain after a climate tipping point, *Nat Food*, 1, 76–83, <https://doi.org/10.1038/s43016-019-0011-3>, 2020.

Ritchie, P. D. L., Clarke, J. J., Cox, P. M., and Huntingford, C.: Overshooting tipping point thresholds in a changing climate, *Nature*, 592, 517–523, <https://doi.org/10.1038/s41586-021-03263-2>, 2021.

Ritchie, P. D. L., Alkhayyon, H., Cox, P. M., and Wieczorek, S.: Rate-induced tipping in natural and human systems, *Earth Syst. Dynam.*, 14, 669–683, <https://doi.org/10.5194/esd-14-669-2023>, 2023.

Ritchie, P. D. L., Huntingford, C., and Cox, P.: ESD Ideas: Climate tipping is not instantaneous — the duration of an overshoot matters, <https://doi.org/10.5194/egusphere-2024-3023>, 2024.

Robinson, A., Calov, R., and Ganopolski, A.: Multistability and critical thresholds of the Greenland ice sheet, *Nature Clim. Change*, 2, 429–432, <https://doi.org/10.1038/nclimate1449>, 2012.

- 805 Robson, J., Menary, M. B., Sutton, R. T., Meeking, J., Gregory, J. M., Jones, C., Sinha, B., Stevens, D. P., and Wileox, L. J.: The Role of Anthropogenic Aerosol Forcing in the 1850–1985 Strengthening of the AMOC in CMIP6 Historical Simulations, *Journal of Climate*, 35, 3243–3263, <https://doi.org/10.1175/jcli-d-22-0124.1>, 2022.
- Romanou, A., Rind, D., Jonas, J., Miller, R., Kelley, M., Russell, G., Orbe, C., Nazarenko, L., Latta, R., and Schmidt, G. A.: Stochastic Bifurcation of the North Atlantic Circulation under a Midrange Future Climate Scenario with the NASA GISS ModelE, *Journal of Climate*, 36, 6141–6161, <https://doi.org/10.1175/jcli-d-22-0536.1>, 2023.
- 810 Romanou, A., Hegerl, G. C., Seneviratne, S. I., Abis, B., Bastos, A., Conversi, A., Landolfi, A., Kim, H., Lerner, P. E., Mekus, J., Otto-Bliesner, B. L., Pausata, F. S. R., Pinto, I., and Suarez-Gutierrez, L.: Extreme Events Contributing to Tipping Elements and Tipping Points, *Surv Geophys*, 46, 375–420, <https://doi.org/10.1007/s10712-024-09863-7>, 2025.
- Rooth, C.: Hydrology and ocean circulation, *Progress in Oceanography*, 11, 131–149, [https://doi.org/10.1016/0079-6611\(82\)90006-4](https://doi.org/10.1016/0079-6611(82)90006-4), 1982.
- 815 Rugenstein, M., Bloch-Johnson, J., Gregory, J., Andrews, T., Mauritsen, T., Li, C., Frölicher, T. L., Paynter, D., Danabasoglu, G., Yang, S., Dufresne, J., Cao, L., Schmidt, G. A., Abe-Ouchi, A., Geoffroy, O., and Knutti, R.: Equilibrium Climate Sensitivity Estimated by Equilibrating Climate Models, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2019gl083898>, 2020.
- 820 Sanderson, B. M., Brovkin, V., Fisher, R., Hohn, D., Ilyina, T., Jones, C., Koenigk, T., Koven, C., Li, H., Lawrence, D., Lawrence, P., Liddicoat, S., MacDougall, A., Mengis, N., Nicholls, Z., O'Rourke, E., Romanou, A., Sandstad, M., Schwinger, J., Seferian, R., Sentman, L., Simpson, I., Smith, C., Steinert, N., Swann, A., Tjiputra, J., and Ziehn, T.: flat10MIP: An emissions driven experiment to diagnose the climate response to positive, zero, and negative CO₂ emissions, <https://doi.org/10.5194/egusphere-2024-3356>, 2024.
- 825 Santana-Falcón, Y., Yamamoto, A., Lenton, A., Jones, C. D., Burger, F. A., John, J. G., Tjiputra, J., Schwinger, J., Kawamiya, M., Frölicher, T. L., Ziehn, T., and Séférian, R.: Irreversible loss in marine ecosystem habitability after a temperature overshoot, *Commun Earth Environ*, 4, <https://doi.org/10.1038/s43247-023-01002-1>, 2023.
- Scheffer, M., Carpenter, S. R., Dakos, V., and Van Nes, E. H.: Generic Indicators of Ecological Resilience: Inferring the Chance of a Critical Transition, *Annu. Rev. Ecol. Evol. Syst.*, 46, 145–167, <https://doi.org/10.1146/annurev-ecolsys-112414-054242>, 2015.
- 830 Schleussner, C. F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., Ciais, P., Frölicher, T. L., Fuss, S., Gasser, T., Gidden, M. J., Kropf, C. M., Lacroix, F., Lamboll, R., Martyr, R., Maussion, F., McCaughey, J. W., Meinshausen, M., Mengel, M., Nicholls, Z., Quileuille, Y., Sanderson, B., Seneviratne, S. I., Sillmann, J., Smith, C. J., Steinert, N. J., Theokritoff, E., Warren, R., Price, J., and Rogelj, J.: Overconfidence in climate overshoot, *Nature*, 634, 366–373, <https://doi.org/10.1038/s41586-024-08020-9>, 2024.
- 835 Schwinger, J. and Tjiputra, J.: Ocean Carbon Cycle Feedbacks Under Negative Emissions, *Geophysical Research Letters*, 45, 5062–5070, <https://doi.org/10.1029/2018gl077790>, 2018.

Sgubin, G., Swingedouw, D., Drijfhout, S., Mary, Y., and Bennabi, A.: Abrupt cooling over the North Atlantic in modern climate models, *Nat Commun*, 8, <https://doi.org/10.1038/neomms14375>, 2017.

1840 Sgubin, G., Swingedouw, D., Dayon, G., García De Cortázar-Atauri, I., Ollat, N., Pagé, C., and Van Leeuwen, C.: The risk of tardive frost damage in French vineyards in a changing climate, *Agricultural and Forest Meteorology*, 250–251, 226–242, <https://doi.org/10.1016/j.agrformet.2017.12.253>, 2018.

Sgubin, G., Swingedouw, D., García De Cortázar-Atauri, I., Ollat, N., and Van Leeuwen, C.: The Impact of Possible Decadal-Scale Cold Waves on Viticulture over Europe in a Context of Global Warming, *Agronomy*, 9, 397, <https://doi.org/10.3390/agronomy9070397>, 2019.

1845 Silvy, Y., Frölicher, T. L., Terhaar, J., Joos, F., Burger, F. A., Lacroix, F., Allen, M., Bernardello, R., Bopp, L., Brovkin, V., Buzan, J. R., Cadule, P., Dix, M., Dunne, J., Friedlingstein, P., Georgievski, G., Hajima, T., Jenkins, S., Kawamiya, M., Kiang, N. Y., Lapin, V., Lee, D., Lerner, P., Mengis, N., Monteiro, E. A., Paynter, D., Peters, G. P., Romanou, A., Schwinger, J., Sparrow, S., Stofferahn, E., Tjiputra, J., Tourigny, E., and Ziehn, T.: AERA-MIP: emission pathways, remaining budgets, and carbon cycle dynamics compatible with 1.5 and 2 °C global warming stabilization, *Earth Syst. Dynam.*, 15, 1591–1628, <https://doi.org/10.5194/esd-15-1591-2024>, 2024.

Smith, C. J. and Forster, P. M.: Suppressed Late-20th Century Warming in CMIP6 Models Explained by Forcing and Feedbacks, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2021gl094948>, 2021.

Solomon, S.: The discovery of the Antarctic ozone hole, *Nature*, 575, 46–47, <https://doi.org/10.1038/d41586-019-02837-5>, 2019.

1850 Soultan, A., Pavón Jordán, D., Bradter, U., Sanderecock, B. K., Hochachka, W. M., Johnston, A., Brommer, J., Gaget, E., Keller, V., Knaus, P., Aghababayan, K., Maxhuni, Q., Vintchevski, A., Nagy, K., Raudonikis, L., Balmer, D., Noble, D., Leitão, D., Øien, I. J., Shimmings, P., Sultanov, E., Caffrey, B., Boyle, K., Radišić, D., Lindström, Å., Veleviski, M., Pladevall, C., Brotons, L., Karel, Š., Rajković, D. Z., Chodkiewicz, T., Wilk, T., Szép, T., Van Turnhout, C., Foppen, R., Burfield, I., Vikström, T., Mazal, V. D., Eaton, M., Vorisek, P., Lehtikoinen, A., Herrando, S., Kuzmenko, T., Bauer, H. G., Kalyakin, M. V., Voltzit, O. V., Sjeničić, J., and Pärt, T.: The future distribution of wetland birds breeding in Europe validated against observed changes in distribution, *Environ. Res. Lett.*, 17, 024025, <https://doi.org/10.1088/1748-9326/ac4ebe>, 2022.

Staal, A., Fetzner, I., Wang-Erlandsson, L., Bosmans, J. H. C., Dekker, S. C., Van Nes, E. H., Rockström, J., and Tuinenburg, O. A.: Hysteresis of tropical forests in the 21st century, *Nat Commun*, 11, <https://doi.org/10.1038/s41467-020-18728-7>, 2020.

1865 Stocker, T. F. and Schmittner, A.: Influence of CO₂-emission rates on the stability of the thermohaline circulation, *Nature*, 388, 862–865, <https://doi.org/10.1038/42224>, 1997.

Stommel, H.: Thermohaline Convection with Two Stable Regimes of Flow, *Tellus*, 13, 224–230, <https://doi.org/10.1111/j.2153-3490.1961.tb00079.x>, 1961.

1870 Swaminathan, R., Parker, R. J., Jones, C. G., Allan, R. P., Quaife, T., Kelley, D. I., Mora, L. de, and Walton, J.: The Physical Climate at Global Warming Thresholds as Seen in the U.K. Earth System Model, *Journal of Climate*, 35, 29–48, <https://doi.org/10.1175/JCLI-D-21-0234.1>, 2022.

- Swingedouw, D., Braconnot, P., Delecluse, P., Guilyardi, E., and Marti, O.: Quantifying the AMOC feedbacks during a 2×CO₂ stabilization experiment with land-ice melting, *Clim Dyn*, 29, 521–534, <https://doi.org/10.1007/s00382-007-0250-0>, 2007.
- Swingedouw, D., Hefjika Speranza, C., Bartsch, A., Durand, G., Jamet, C., Beaugrand, G., and Conversi, A.: Early Warning from Space for a Few Key Tipping Points in Physical, Biological, and Social-Ecological Systems, *Surv Geophys*, 41, 1237–1284, <https://doi.org/10.1007/s10712-020-09604-6>, 2020.
- Swingedouw, D., Bily, A., Esquerdo, C., Borehert, L. F., Sgubin, G., Mignot, J., and Menary, M.: On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models, *Annals of the New York Academy of Sciences*, 1504, 187–201, <https://doi.org/10.1111/nyas.14659>, 2021.
- Tamarin-Brodsky, T., Hodges, K., Hoskins, B. J., and Shepherd, T. G.: Changes in Northern Hemisphere temperature variability shaped by regional warming patterns, *Nat. Geosci.*, 13, 414–421, <https://doi.org/10.1038/s41561-020-0576-3>, 2020.
- Taylor, P. C., Boeke, R. C., Boisvert, L. N., Feldl, N., Henry, M., Huang, Y., Langen, P. L., Liu, W., Pithan, F., Sejas, S. A., and Tan, I.: Process Drivers, Inter-Model Spread, and the Path Forward: A Review of Amplified Arctic Warming, *Front. Earth Sci.*, 9, <https://doi.org/10.3389/feart.2021.758361>, 2022.
- Tebaldi, C., Ranasinghe, R., Voudoukas, M., Rasmussen, D. J., Vega-Westhoff, B., Kirezci, E., Kopp, R. E., Sriver, R., and Mentaschi, L.: Extreme sea levels at different global warming levels, *Nat. Clim. Chang.*, 11, 746–751, <https://doi.org/10.1038/s41558-021-01127-1>, 2021.
- Terhaar, J., Frölicher, T. L., Aschwanden, M. T., Friedlingstein, P., and Joos, F.: Adaptive emission reduction approach to reach any global warming target, *Nat. Clim. Chang.*, 12, 1136–1142, <https://doi.org/10.1038/s41558-022-01537-9>, 2022.
- Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K., and McGuire, A. D.: Carbon release through abrupt permafrost thaw, *Nat. Geosci.*, 13, 138–143, <https://doi.org/10.1038/s41561-019-0526-0>, 2020.
- Rahmstorf, S.: Is the Atlantic Overturning Circulation Approaching a Tipping Point?, *Oceanog.*, <https://doi.org/10.5670/oceanog.2024.501>, 2024.
- Ureta, C., Ramírez-Barahona, S., Calderón-Bustamante, Ó., Cruz-Santiago, P., Gay-García, C., Swingedouw, D., Defrance, D., and Cuervo-Robayo, A. P.: Evaluation of animal and plant diversity suggests Greenland’s thaw hastens the biodiversity crisis, *Commun Biol*, 5, <https://doi.org/10.1038/s42003-022-03943-3>, 2022.
- Vaittinada-Ayar, P., Bopp, L., Christian, J. R., Ilyina, T., Krasting, J. P., Séférian, R., Tsujino, H., Watanabe, M., Yool, A., and Tjiputra, J.: Contrasting projections of the ENSO-driven CO₂ flux variability in the equatorial Pacific under high-warming scenario, *Earth Syst. Dynam.*, 13, 1097–1118, <https://doi.org/10.5194/esd-13-1097-2022>, 2022.
- Valdes, P.: Built for stability, *Nature Geosci.*, 4, 414–416, <https://doi.org/10.1038/ngeo1200>, 2011.
- Van Breedam, J., Goelzer, H., and Huybrechts, P.: Semi-equilibrated global sea-level change projections for the next 10 000 years, *Earth Syst. Dynam.*, 11, 953–976, <https://doi.org/10.5194/esd-11-953-2020>, 2020.
- Van Nes, E. H., Arani, B. M. S., Staal, A., Van Der Bolt, B., Flores, B. M., Bathiany, S., and Scheffer, M.: What Do You Mean, ‘Tipping Point’?, *Trends in Ecology & Evolution*, 31, 902–904, <https://doi.org/10.1016/j.tree.2016.09.011>, 2016.

Van Vuuren, D., O'Neill, B., Tebaldi, C., Chini, L., Friedlingstein, P., Hasegawa, T., Riahi, K., Sanderson, B., Govindasamy, B., Bauer, N., Eyring, V., Fall, C., Frieler, K., Gidden, M., Gohar, L., Jones, A., King, A., Knutti, R., Kriegler, E., Lawrence, P., Lennard, C., Lowe, J., Mathison, C., Mehmood, S., Prado, L., Zhang, Q., Rose, S., Ruane, A., Schleussner, C. F., Seferian, R., Sillmann, J., Smith, C., Sörensson, A., Paniekal, S., Tachiiri, K., Vaughan, N., Vishwanathan, S., Yokohata, T., and Ziehn, T.: The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7), <https://doi.org/10.5194/egusphere-2024-3765>, 2025.

van Westen, R. M., Vanderborgh, E. Y. P., Kliphuis, M., and Dijkstra, H. A.: Substantial Risk of 21st Century AMOC Tipping even under Moderate Climate Change, <https://doi.org/10.48550/ARXIV.2407.19909>, 2024a.

van Westen, R. M., Kliphuis, M., and Dijkstra, H. A.: Physics-based early warning signal shows that AMOC is on tipping course, *Sci. Adv.*, 10, <https://doi.org/10.1126/sciadv.adk1189>, 2024b.

Vasilakopoulos, P., Raitos, D. E., Tzanatos, E., and Maravelias, C. D.: Resilience and regime shifts in a marine biodiversity hotspot, *Sci Rep.*, 7, <https://doi.org/10.1038/s41598-017-13852-9>, 2017.

Wehrli, K., Luo, F., Hauser, M., Shioyama, H., Tokuda, D., Kim, H., Coumou, D., May, W., Le Sager, P., Selten, F., Martius, O., Vautard, R., and Seneviratne, S. I.: The ExtremeX global climate model experiment: investigating thermodynamic and dynamic processes contributing to weather and climate extremes, *Earth Syst. Dynam.*, 13, 1167–1196, <https://doi.org/10.5194/esd-13-1167-2022>, 2022.

Wei, M., Li, S., Zhu, L., Lu, X., Li, H., and Feng, J.: Continuous Abrupt Vegetation Shifts in the Global Terrestrial Ecosystem, *Ecology Letters*, 28, <https://doi.org/10.1111/ele.70069>, 2025.

Weijer, W., Cheng, W., Garuba, O. A., Hu, A., and Nadiga, B. T.: CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2019gl086075>, 2020.

Wileox, L. J., Allen, R. J., Samset, B. H., Bollasina, M. A., Griffiths, P. T., Keeble, J., Lund, M. T., Makkonen, R., Merikanto, J., O'Donnell, D., Paynter, D. J., Persad, G. G., Rumbold, S. T., Takemura, T., Tsigaridis, K., Undorf, S., and Westervelt, D. M.: The Regional Aerosol Model Intercomparison Project (RAMIP), *Geosci. Model Dev.*, 16, 4451–4479, <https://doi.org/10.5194/gmd-16-4451-2023>, 2023.

Williams, A. S. and Igel, A. L.: Cloud Top Radiative Cooling Rate Drives Non-Precipitating Stratiform Cloud Responses to Aerosol Concentration, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2021gl094740>, 2021.

Williams, R. G., Ceppi, P., and Katavouta, A.: Controls of the transient climate response to emissions by physical feedbacks, heat uptake and carbon cycling, *Environ. Res. Lett.*, 15, 0940e1, <https://doi.org/10.1088/1748-9326/ab97e9>, 2020.

Williams, R. G., Goodwin, P., Ceppi, P., Jones, C. D., and MacDougall, A.: A normalised framework for the Zero Emissions Commitment, <https://doi.org/10.5194/egusphere-2025-800>, 2025.

Winkelmann, R., Dennis, D. P., Donges, J. F., Loriani, S., Klose, A. K., Abrams, J. F., Alvarez-Solas, J., Albrecht, T., Armstrong-McKay, D., Bathiany, S., Blasco-Navarro, J., Brovkin, V., Burke, E., Danabasoglu, G., Donner, R. V., Drüke, M., Georgievski, G., Goelzer, H., Harper, A. B., Hegerl, G., Hirota, M., Hu, A., Jackson, L. C., Jones, C., Kim, H., Koenigk, T.,

- 1940 Lawrence, P., Lenton, T. M., Liddy, H., Lieón-Saláiz, J., Menthon, M., Montoya, M., Nitzbon, J., Nowicki, S., Otto-Bliesner, B., Pausata, F., Rahmstorf, S., Ramin, K., Robinson, A., Roekström, J., Romanou, A., Sakschewski, B., Schädel, C., Sherwood, S., Smith, R. S., Steinert, N. J., Swingedouw, D., Willeit, M., Weijer, W., Wood, R., Wyser, K., and Yang, S.: The Tipping Points—Modelling—Interecomparison—Project (TIPMIP): Assessing tipping point risks in the Earth system, <https://doi.org/10.5194/egusphere-2025-1899>, 2025.
- 1945 Winton, M., Griffies, S. M., Samuels, B. L., Sarmiento, J. L., and Frölicher, T. L.: Connecting Changing Ocean Circulation with Changing Climate, *Journal of Climate*, 26, 2268–2278, <https://doi.org/10.1175/jcli-d-12-00296.1>, 2013.
- Wu, M., Smith, B., Schurgers, G., Ahlström, A., and Rummukainen, M.: Vegetation–Climate Feedbacks Enhance Spatial Heterogeneity of Pan-Amazonian Ecosystem States Under Climate Change, *Geophysical Research Letters*, 48, <https://doi.org/10.1029/2020gl09200>, 2021.
- 1950 Wunderling, N., Staal, A., Sakschewski, B., Hirota, M., Tuinenburg, O. A., Donges, J. F., Barbosa, H. M. J., and Winkelmann, R.: Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest, *Proc. Natl. Acad. Sci. U.S.A.*, 119, <https://doi.org/10.1073/pnas.2120777119>, 2022.
- Wunderling, N., Von Der Heydt, A. S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., Brunetti, M., Couplet, V., Kleinen, T., Lear, C. H., Lohmann, J., Roman Cuesta, R. M., Sinet, S., Swingedouw, D., Winkelmann, R., Anand, P.,
- 1955 Barichevich, J., Bathiany, S., Baudena, M., Bruun, J. T., Chiessi, C. M., Coxall, H. K., Doequier, D., Donges, J. F., Falkena, S. K. J., Klose, A. K., Obura, D., Rocha, J., Rynders, S., Steinert, N. J., and Willeit, M.: Climate tipping point interactions and cascades: a review, *Earth Syst. Dynam.*, 15, 41–74, <https://doi.org/10.5194/esd-15-41-2024>, 2024.
- Zhao, Y., Liu, Y., Guo, Z., Fang, K., Li, Q., and Cao, X.: Abrupt vegetation shifts caused by gradual climate changes in central Asia during the Holocene, *Sci. China Earth Sci.*, 60, 1317–1327, <https://doi.org/10.1007/s11430-017-9047-7>, 2017.
- 1960 Zickfeld, K. and Herrington, T.: The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission, *Environ. Res. Lett.*, 10, 031001, <https://doi.org/10.1088/1748-9326/10/3/031001>, 2015.
- Zickfeld, K., Azevedo, D., Mathesius, S., and Matthews, H. D.: Asymmetry in the climate–carbon cycle response to positive and negative CO₂ emissions, *Nat. Clim. Chang.*, 11, 613–617, <https://doi.org/10.1038/s41558-021-01061-2>, 2021.