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LETTER

Mutual stabilization of AMOC and GrIS due to different transient response to warming

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Abstract

Interactions between The Atlantic Meridional Overturning Circulation (AMOC) And The Greenland Ice-Sheet (GrIS), both considered major tipping elements in the Earth system, are critical for understanding their future evolution under anthropogenic climate change. As global warming progresses, the potential weakening of the AMOC raises concerns that meltwater from the disintegrating GrIS could trigger a complete AMOC shutdown. Here, we assess the processes and feedback mechanisms that may either accelerate or stabilize these two Earth system components under idealized future scenarios in an ice-sheet coupled Earth system model of intermediate complexity with perturbed parameter ensembles. Our findings indicate that, under a moderate idealized scenario ($2\times CO_{2,PI}$, corresponding to $\sim$3 °C global mean warming), GrIS meltwater alone is unlikely to trigger an AMOC collapse. However, this risk increases with higher emissions. Notably, the delayed GrIS response to the warming results in peak meltwater fluxes entering the North Atlantic only when the AMOC is already in its recovery phase, Thereby reducing the likelihood of collapse. Additionally, the system is further stabilized by the cooling induced by the thermal bipolar seesaw. This cooling is sufficiently strong that, in the event of a future AMOC collapse, GrIS melting would effectively cease for $\sim$3 °C warming, and its disintegration would be substantially delayed even under higher warming levels. Nonetheless, rapid CO_2 reduction remains essential to prevent irreversible state transitions of both the AMOC and GrIS.

1. Introduction

The ongoing anthropogenic climate change has raised concerns about potentially triggering abrupt and practically irreversible transitions in key components of the Earth's climate system [1–3]. Among these critical tipping elements, the Atlantic Meridional Overturning Circulation (AMOC) and continental ice-sheets are particularly impactful, each capable of substantially influencing the climate system at global scale [4, 5]. Importantly, these tipping elements do not respond to warming in isolation, but interactions between them may either accelerate their trajectory towards crossing a critical threshold or instead stabilize them, averting irreversible state transitions [6–8]. Evidence for the possibility of abrupt climate changes comes from paleoclimate proxy records [9, 10], from theoretical considerations [11], but also from Earth system models [12]. Yet, our understanding of the interactions between tipping elements under future climate scenarios remains limited.

The AMOC is an integral part of the global ocean circulation, responsible for the majority of the inter-hemispheric transport of heat, nutrients, and carbon in the Atlantic Ocean [13, 14]. It is characterized by northward-flowing surface currents that return southward in the deep ocean. This circulation drives the thermal bipolar seesaw [15], where an abrupt cooling in the North Atlantic due to a reduction or shutdown of the AMOC leads to heat accumulation and gradual warming in the south, and vice versa. This leaves a global imprint of these events. Paleoceanographic reconstructions and historical data indicate that the AMOC has persisted continuously in its strong circulation state since the end of the last deglaciation [16–18]. However, there are indications that it may have begun to weaken in recent decades as anthropogenic climate change has accelerated [19], although direct observational data, albeit comparatively short, have not yet revealed a significant trend [20, 21]. In the past, abrupt AMOC weakening was primarily triggered by large meltwater influx into the North Atlantic from disintegrating continental ice-sheets [22–24], limiting deep convection for centuries to millennia. In contrast, the rapid warming that commenced in the late 19th century and is projected to continue into the second half of the 21st century appears to be weakening the AMOC primarily due to thermal effects and enhanced by an increased meridional moisture transport in the atmosphere [25, 26]. However, the Greenland ice-sheet (GrIS) has been losing mass for the last two decades due to global warming [27], and melt rates are expected to increase over the coming centuries [28–30]. This raises the question of whether the decaying GrIS could be the trigger to collapse the already weakening AMOC at some stage. As only very few coupled Earth system models can simulate multi-centennial climate evolution [31], feedbacks between the AMOC and GrIS remain only poorly assessed, with uncertainties further increasing due to limited constraints on future GrIS melt.

Here, we address the large uncertainties persisting in our understanding of the interactions between the two major tipping elements of the AMOC and the GrIS under idealized future climate scenarios. By employing an Earth system model of intermediate complexity coupled to a state-of-the-art ice-sheet model [32], we directly assess the impact of realistic meltwater fluxes on the future AMOC evolution and how this in turn influences the GrIS. We evaluate the feedback mechanisms governing the interactions between these two tipping elements and explore the impact of ice-sheet uncertainties through extensive perturbed parameter ensembles.

2. Methods

2.1. Model description

We employ the Bern3D v3 Earth system model of intermediate complexity [32], which comprises a dynamic geostrophic-frictional balance ocean, thermodynamic sea-ice component, a single layer energy-moisture balance atmosphere, and the three-dimensional ice-sheet component CISM v2.1 [33]. Due to the simplicity of the atmospheric component, wind stress and cloud cover are prescribed as monthly climatologies [34]. The spatial resolution is 68 × 46 horizontal grid cells on an irregular grid (∼ 5° × 4°) with 40 logarithmically scaled depth layers in the ocean component. The ice-sheet model only covers the domain of Greenland on a 10 km × 10 km grid with 11 σ-levels on a stereographic projection with ice dynamics solved with the depth-integrated viscosity approximation [33]. The ocean/atmosphere and ice-sheet components are bi-directionally coupled exchanging fields once a year (see Pöppelmeier *et al* [32] for more details on the coupling approach). The surface mass balance (SMB) is calculated with a positive degree day (PDD) method, that calculates the ablation from daily air temperature variations [35]. The geothermal heat flux is set uniformly to 0.05 W m^{-2}. The surface ice-sheet is forced with ERA5 climatologies of air temperature and precipitation to which Bern3D anomalies relative to pre-industrial are added. Meltwater from the GrIS is routed to the closest ocean grid-cell based on topography. The isostatic adjustment assumes a relaxation time of 5000 years and is updated every 10 years. Ice advancing beyond the observational extent is immediately calved. The equilibrium climate sensitivity of the coupled model is 3.4 K [32], close to multimodel mean of the most recent assessment of the IPCC [36].

2.2. Model experiments

All experiments are branched off from the steady-state pre-industrial simulation here defined as 1765 CE, and greenhouse gas concentrations of CO_2 = 278.05 ppm, CH_4 = 721.9 ppb, and N_2O = 273.0 ppb [37].

We assessed the hysteresis of the GrIS under varying CO_2 levels by incrementally increasing the atmospheric CO_2 concentrations from 300 ppm to 480 ppm in steps of 20 ppm, with additional steps close to the tipping points for each of the ten best performing ensemble members. Each simulation was run for 30 kyr (figure 2). The return path from high to low CO_2 concentrations was initialized from a virtually ice-free Greenland state. The AMOC hysteresis was assessed by linearly increasing the North Atlantic freshwater hosing with a rate of 0.03 Sv kyr^{-1} until 0.3 Sv are reached and then decreased with the same rate. This was performed for the three different ocean setups (figures 1(a) and S1).

Additionally, we performed a series of experiments representing idealized future scenarios with the fully coupled setup, characterized by 1%/yr CO_2 increases up to either 2×CO_2(PI) or 4×CO_2(PI), which were run for 3000 years with constant orbital configuration. We explored the sensitivity of the coupled system to the meltwater feedback by either disabling it (no meltwater from the disintegrating ice-sheet reaches the ocean) or applying an additional freshwater hosing flux of 0.2 Sv to the North Atlantic (45–70° N) that is independent of the GrIS evolution and effectively collapses the AMOC as done in classical hosing experiments. For these simulations freshwater is not conserved in the Earth system. These simulations were performed to explore the GrIS response to such an unlikely event, that may not be triggered in the Bern3D model, due to potential model biases.

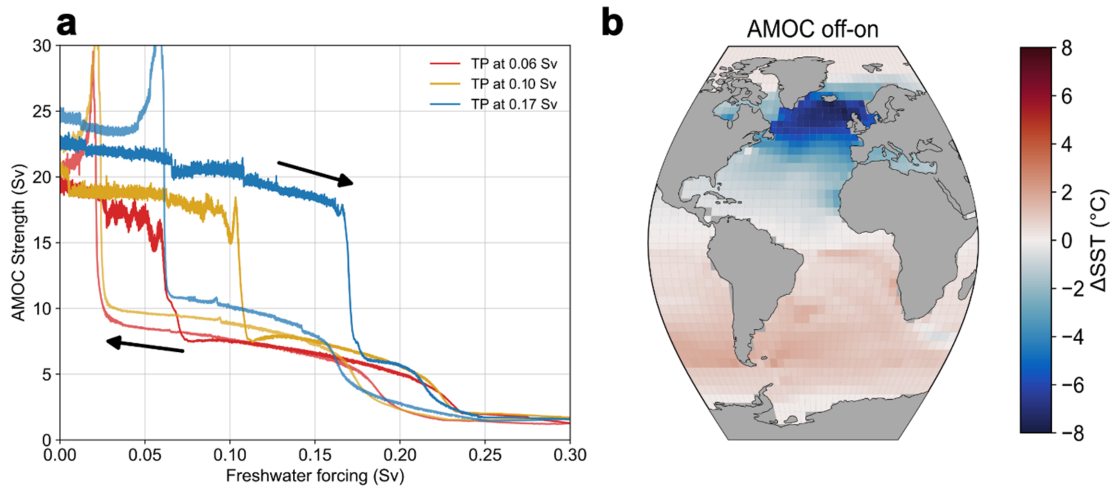

Figure 1. AMOC hysteresis and impact on SST. (a) Hysteresis of the simulated AMOC with respect to freshwater forcing for three different ocean circulation parameter sets. The freshwater forcing was linearly increased with a rate of 0.03 Sv kyr^{-1} up to 0.3 Sv and then reduced at the same rate. See supplementary information for details on the three ocean setups. (**b**) Sea-surface temperature difference (ΔSST) between the pre-industrial state and a fully collapsed AMOC. These correspond to ensemble members x.3, x.2, and x.1, for low, mid, and high tipping points.

Finally, we conducted experiments that include a ramp-down of the elevated CO_2 concentrations after 100 yr and 500 yr back to the PI level. During all transient simulations changes in sea-level due to the disintegrating GrIS did not change the ocean's bathymetry [38].

2.3. Ensemble simulations

The pre-industrial ice-sheet was spun up with a 200-member perturbed ice-sheet parameter ensemble over 30 000 years of which the ten best performing simulations with regard to present-day ice thickness were chosen for further simulations (see supplementary information and figure S3, termed members 1.x to 10.x). This approach was chosen to consider ice-sheet parameter uncertainty in our simulations.

In addition, we explored how different ocean parameter combinations impact AMOC hysteresis through a set of 30 sensitivity tests (see supplementary information for details). For all further simulations, we chose three different parameter combinations that yield a low, mid, and high AMOC tipping point with regard to North Atlantic freshwater forcing (figure 1(a)), termed ensemble members x.3, x.2, and x.1, respectively. The key differences between the parameter combinations are diapycnal diffusivity and inverse minimum drag.

We performed simulations systematically combining the three ocean circulation states and ten GrIS parameter sets, i.e. the full ensemble has 30 members.

3. Results and discussion

3.1. Hysteresis of the AMOC and GrIS

Concern exists that Earth system models may be overly stable regarding the AMOC [39]. To address this, we explore three different ocean parameter setups exhibiting different strengths of AMOC hysteresis. The tipping points of these three setups towards a strongly weakened AMOC with a remaining strength of 5–8 Sv are at 0.06, 0.10, and 0.17 Sv of North Atlantic freshwater forcing, which we term low, mid, and high AMOC tipping, respectively (figure 1(a)). The weakened state is similar in AMOC strength independent of the setups and appears to be an additional stable regime. The AMOC only fully collapses if more than ca. 0.2 Sv of freshwater is applied to the North Atlantic, independent of the ocean parameter setup.

A fully collapsed AMOC causes a maximum sea surface temperature cooling of 8 °C around Iceland due to the thermal bipolar seesaw [15]. Although observational constraints on the modern AMOC hysteresis are lacking, complex Earth system models have demonstrated hysteresis [40], although the precise location of the tipping point relative to forcing levels remains unknown.

The GrIS displays substantially different hysteresis behavior for the ten ensemble members although they all represent the pre-industrial ice-thickness well (figures 2 and S2). The tipping point is crossed abruptly in all setups, at CO_2 levels between 310 and 390 ppm. The shape of the hysteresis is qualitatively similar for the ten members, with members exhibiting the tipping point at high CO_2 concentrations also returning to their pre-industrial state at higher concentrations and vice versa. The recovery occurs not as abruptly in CO_2-space as the disintegration, potentially related to not long enough model run time to reach equilibrium during CO_2 ramp-down and very slow build-up times. Six ensemble members are mono-stable under pre-industrial CO_2 concentrations, two are close to mono-stable, and two bistable. In terms of

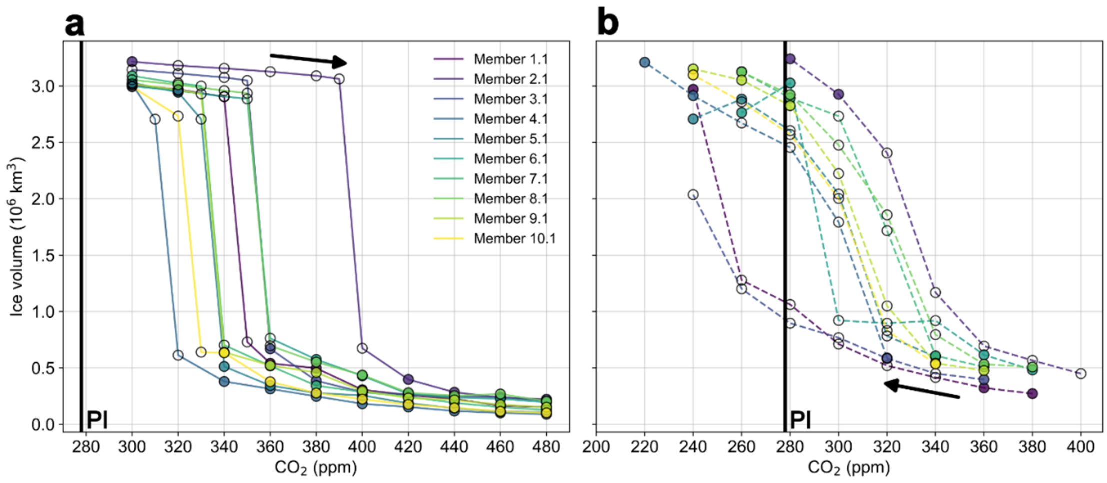

Figure 2. Hysteresis of Greenland ice-sheet. (a) Increasing CO_2 concentrations started from PI conditions. (b) Simulations that continued from a deglaciated state, with CO_2 decreasing. Simulations were run for 30 kyr. Open circles depict bistability while filled circles show where the ice-sheet is monostable.

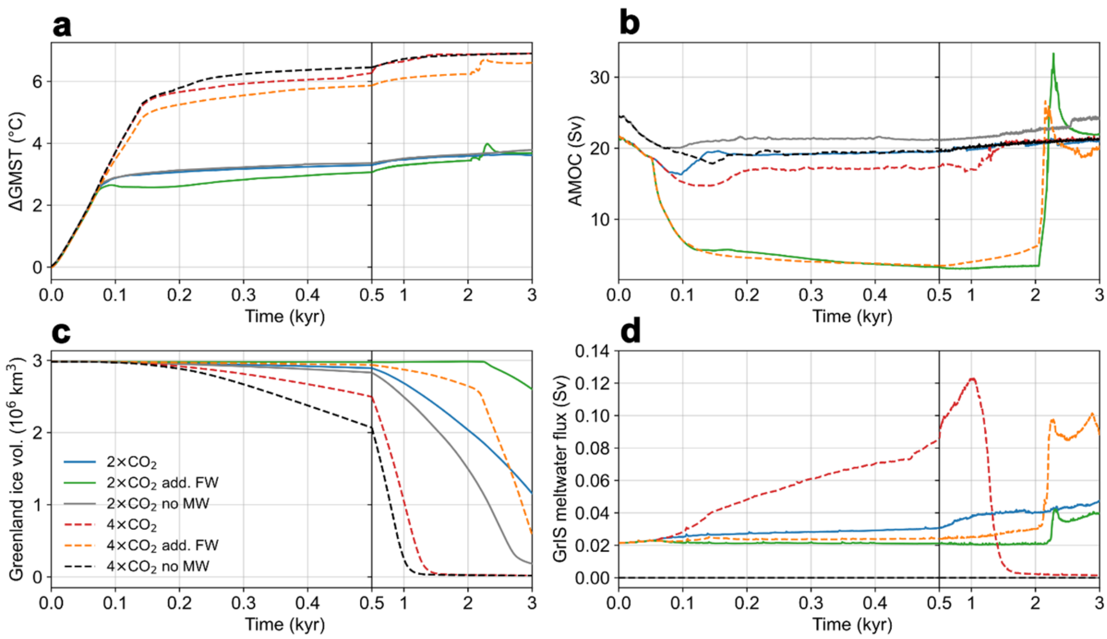

Figure 3. Timeseries of idealized CO_2 experiments for ensemble member 1.1. (a) GMST, (b) AMOC, (c) GrIS ice volume, and (d) GrIS total melt rate. Solid lines depict simulations that follow a 1%/yr 2×CO_2 increase, and dashed lines are 1%/yr 4×CO_2 simulations. See Methods for setup for simulations with no meltwater feedback (no MW) and additional freshwater hosing (add FW). All simulations were performed for the best GrIS ensemble member and AMOC with high tipping point. For simulations with low and mid AMOC tipping thresholds, see figures S4 and S5.

Global Mean Surface Temperature (GMST) warming relative to pre-industrial, the CO_2 concentrations of the tipping points correspond to between ∼0.5 °C and 2 °C warming (figure S1). During the last interglacial (130–120 kyr ago), warming levels reached 0.5–1.5 °C [41], which was accompanied by substantial GrIS mass loss, with estimates ranging from 0.5 to 5 m sea-level equivalent [42–44]. Thus, the constraint from the GrIS evolution of the last interglacial falls between the GrIS ensemble members used here. Yet, it is important to note that the last interglacial was too short for the GrIS to reach its equilibrium state, while the different orbital configuration might have promoted more summer melt [45] than today's configuration, making direct comparisons challenging.

3.2. Stabilizing feedbacks between the AMOC and GrIS

The idealized anthropogenic CO_2 scenarios drive increasing temperatures, resulting in both accelerated GrIS melting and AMOC weakening (figure 3). When CO_2 concentrations are stabilized after 70 yr and 140 yr for a doubling and quadrupling, respectively, GMST has increased by about 2.7 °C and 5.5 °C.

In the following centuries, temperatures rise by an additional 1–1.5 °C, although the exact progression is influenced by the evolution of the AMOC. These scenarios are comparable to 'middle-of-the-road' and 'high-emission' scenarios of the IPCC [36] but are extended here into the far future for 3000 years.

Here we first discuss the results of the best ensemble member in combination with a high AMOC tipping point (member 1.1). The responses to warming differ substantially between the AMOC and GrIS. The AMOC weakens immediately, reaching its minimum strength when CO_2 concentrations stop increasing, followed by a relatively rapid recovery over 200 yr for the 2×CO_2 scenario. However, the pre-industrial strength is only reached again after 1500 yr for the 4×CO_2 scenario. For the setup with the most sensitive AMOC, the recovery is about 100 yr slower in the 2×CO_2 scenario (figure S5). In contrast, the GrIS exhibits a delayed response to the warming. At steady-state meltwater fluxes (which includes calving, and all frozen and liquid discharge) are about 0.02 Sv balanced by surface accumulation. At the year 100, the meltwater flux has increased only slightly by between 100 and 250 Gt yr^{-1} for the 2×CO_2 and 4×CO_2 scenarios, respectively, comparable to the observed inter-annual variability between 86 and 444 Gt yr^{-1} [46]. Subsequently, melt rates continue to rise until the end of the simulations for 2×CO_2, but peak at year 1000 for 4×CO_2 (figure 3(d)). This results in maximum meltwater fluxes into the North Atlantic and Arctic of 0.05 Sv and 0.12 Sv (for 2×CO_2 and 4×CO_2, respectively), with the latter comparable to the minimum freshwater hosing tested in the North Atlantic Hosing Model Intercomparison Project [47]. The entire GrIS vanishes after approximately 1200 yr under stabilized 4×CO_2 but only melts to 40% of its initial size for 2×CO_2.

Previously, it has been hypothesized that the coupled GrIS AMOC system might exhibit cascading tipping points [4, 7], initiated by accelerated GrIS melt pushing the AMOC past its critical threshold into a collapsed state [48–50]. These studies highlight that including some form of idealized GrIS melt may trigger a full AMOC collapse compared to a setup without such meltwater fluxes. Yet notably, these studies are commonly not performed in a coupled setup, lacking important feedbacks and characteristic transient behavior. Two factors prevent this cascading effect from manifesting in the Bern3D model. First, even the maximum excess meltwater flux of 0.10 Sv (0.12 Sv minus 0.02 Sv present at steady-state) of the 4×CO_2 scenario is less than is needed to collapse the AMOC as determined under pre-industrial conditions (figure 1(a)). Furthermore, the relatively short time of a few centuries, during which this flux is maintained, may not be sufficient to lead to a transgression of the tipping point even for the setup with a low AMOC tipping point at 0.06 Sv under pre-industrial conditions [51]. Second, the different response times of these two Earth system components result in the maximum meltwater fluxes not reaching the ocean during the AMOC's most vulnerable phase, i.e. after 100–200 years when the warming-induced minimum strength is reached. Instead, meltwater rates only peak when the AMOC is already in its recovery phase. This slower increase in meltwater fluxes is due to the melt-elevation feedback, which effectively leads to a continuous increase in the temperature at the surface of the ice-sheet.

While GrIS meltwater exerts a destabilizing effect on the AMOC, the reverse relationship does not hold true. A weakened AMOC induces cooling in the North Atlantic relative to a scenario without such weakening (or rather a locally diminished warming in the present scenarios, see figure 4(c)) because of the greatly reduced northern heat transport [15], which in turn limits the acceleration of GrIS melt.

In a setup where no meltwater from the disintegrating GrIS reaches the ocean (*no MW*), the AMOC recovers substantially faster, particularly for the high-emission scenario and low AMOC tipping point (figure S5), with recovery occurring about 200 years earlier than in the standard setup (figure 3(b)). The effect is strongly diminished in the setups with AMOC tipping point at higher freshwater forcing levels (cf figures 3 and S3). The difference between the *no MW* and fully coupled experiments shows that the maximum AMOC weakening due to meltwater is between 2 and 10 Sv primarily depending on the ocean setup and not on CO_2 concentrations (figures 3, S4 and S5). Although this large effect highlights the importance of meltwater feedbacks for the AMOC's response to climate change, it is crucial to note that it only becomes important after ∼150 yr. In these sensitivity tests, the faster AMOC recovery and the consequently diminished northern heat transport lead to more rapid GrIS melting, resulting in its complete disintegration a few hundred years earlier than in scenarios where the meltwater feedback is enabled. In experiments with additional hosing that virtually collapses the AMOC, the effect is even more pronounced. Due to the stronger cooling from the enhanced bipolar seesaw effect, the GrIS melt rates decrease substantially, even halting the melting in the 2×CO_2 scenario and strongly limiting it in the 4×CO_2 scenario. This effect is non-linear in the Bern3D model, meaning that additional AMOC weakening causes an increasing cooling in the North Atlantic per AMOC change, thereby limiting any further GrIS melt. This non-linear effect stabilizes the circulation above the critical thresholds. As soon as the AMOC recovers, GrIS melting continues as before.

The non-linear relationship between AMOC strength and North Atlantic SST anomaly, assessed from the quasi-steady-states of the hysteresis simulation, reveals a seven-fold increase in SST cooling per Sv as the AMOC strength decreases from 15 Sv to

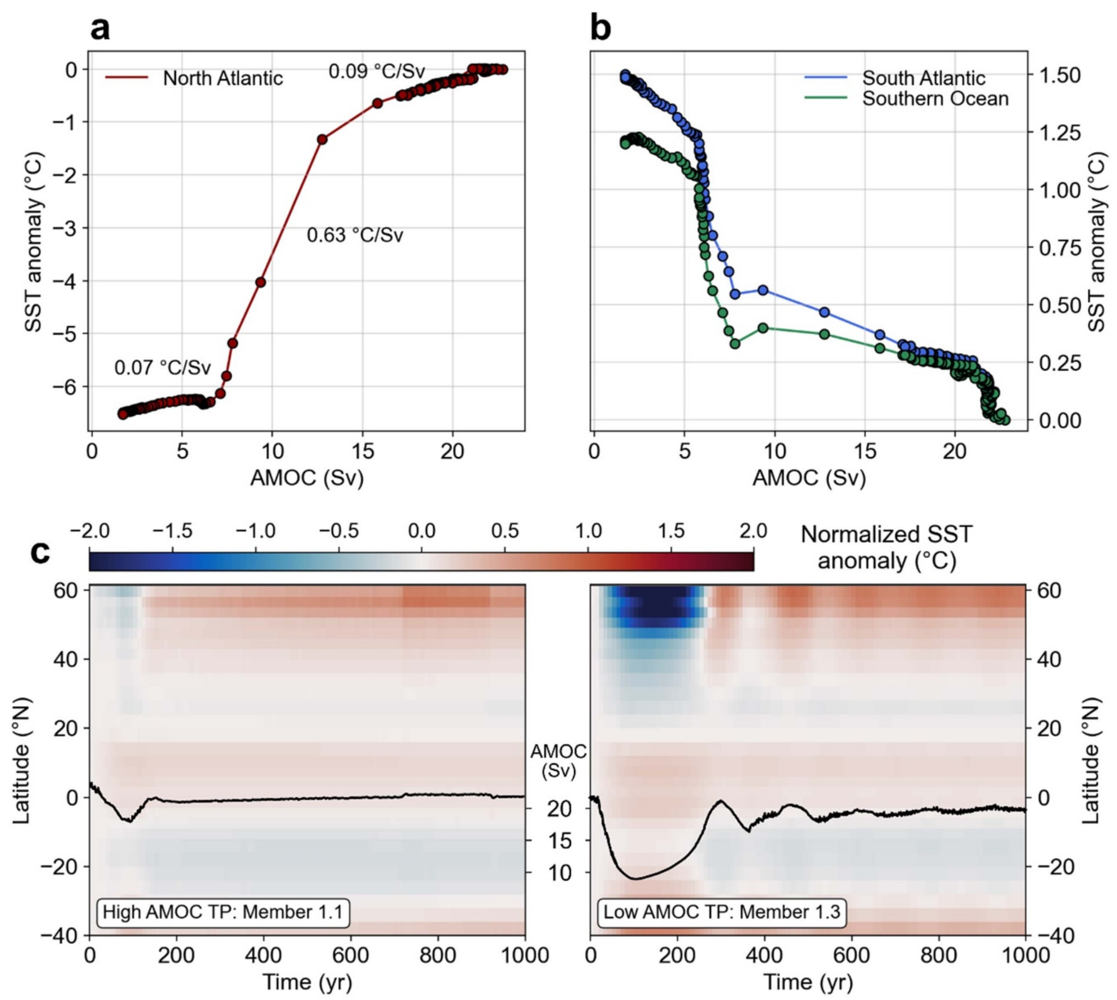

Figure 4. Effect of the thermal bipolar seesaw. (a) Relationship between AMOC strength and North Atlantic (40–75°N) SST sampled every 50 yr from the hysteresis simulation with high AMOC tipping point (circles, see figures 1 and 3, ensemble member 1.1). (b) Same as panel a, but for the South Atlantic (32–48° S) and Southern Ocean (south of 48° S). (c) Hovmoller diagrams depicting zonally normalized SST anomalies over the first 1000 yrs with high AMOC tipping point (left) and low tipping point (right) for the $2\times CO_2$ scenario. Black lines mark the AMOC timeseries for both simulations.

10 Sv (figure 4(a)). Consequently, any AMOC weakening towards the critical threshold induces increased North Atlantic cooling, which in turn limits GrIS melt and thus prevents the AMOC from surpassing its tipping point. A further change in slope of this relationship, reverting to smaller SST changes, coincides with the additional stable regime (see figure 1(a)). This stabilizing feedback also contributes to the delayed ice-sheet response to the warming, as the rapid decline of the AMOC during the global warming phase limits the regional warming experienced by Greenland (figures 3(c) and (d)). In addition, the impact of GrIS meltwater on the AMOC is strongly dependent on the present-day ocean state. The lower the freshwater forcing level required to tip the AMOC, the more sensitive the AMOC is to meltwater, as determined by the comparison to the experiments without the meltwater feedback (cf figures 3, 4 and S5). But a more sensitive AMOC also stabilizes the GrIS more, hence reducing the meltwater fluxes.

3.3. Assessing uncertainties through perturbed parameters

Both the ocean and ice-sheet models employed here suffer from some limitations (see Pöppelmeier *et al* [32] for details). Like many Earth system models, the Bern3D model has biases in surface temperature and salinity as well as in the net freshwater/salt import/export into the Atlantic, which influences the AMOC's stability conditions. The coarse spatial resolution may bias the AMOC's response to warming and freshwater, although a clear improvement with higher resolutions has not yet been found [52]. In addition, we employ the PDD method to calculate SMB of the ice sheet, which is an empirical approach, with limitations when applied outside present-day climate. Other ice-sheet parameters, and in particular basal friction, also remain uncertain. To assess the impact of these uncertainties, we performed the $2\times CO_2$ and $4\times CO_2$ experiments with all combinations of the ten best performing ice-sheet ensemble members and

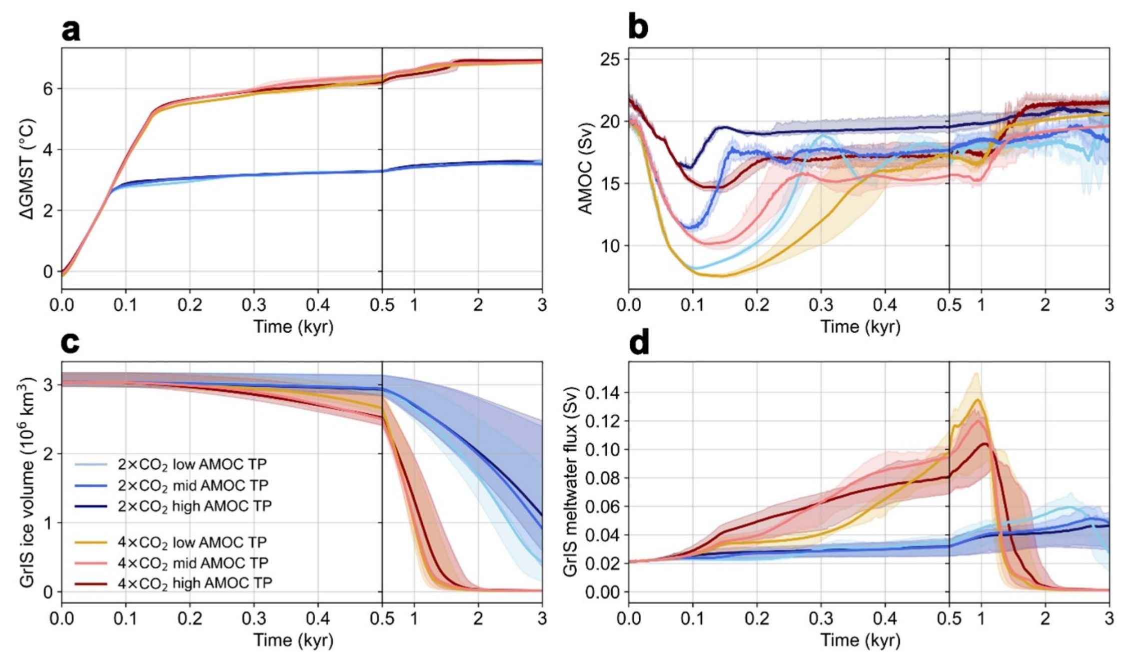

Figure 5. Timeseries of entire ensemble. Experiments following 1%/yr 2 × CO_2 (bluish colors) and 1%/yr 4 × CO_2 increases (red and yellow colors). (a) GMST, (b) AMOC, (c) GrIS ice volume, and (d) total GrIS meltwater flux. The three ocean parameter setups leading to different AMOC tipping thresholds are colored from dark high tipping point to light low tipping point. Shadings indicate ensemble range, while thick lines are the ensemble mean.

three ocean setups for low, intermediate, and high AMOC tipping, characterized in figure 1.

The range of possible GrIS evolutions, primarily originates from the uncertainties in SMB and basal friction in both scenarios, which are substantially larger than the dependency on the AMOC's sensitivity to freshwater. For the middle-of-the-road (2×CO_2) scenario, the difference in GrIS evolution is extensive, resulting in an ice-sheet mass decrease between 19% and 100% at the year 3000 (figure 5(c)). Conversely, uncertainties in the ice-sheet parameters have a much smaller effect in the high-emission scenario (4×CO_2), where the GrIS has vanished before the year 2000 for all ensemble members.

The impact of ice-sheet uncertainty on the AMOC evolution is relatively limited in both emission scenarios (figure 5(b)). For the 2×CO_2 scenario, peak meltwater fluxes are <0.07 Sv for all ensemble members and range from 0.10 to 0.15 Sv in 4×CO_2 scenario. This translates to a total ensemble range in AMOC evolution of <5 Sv, only considering the impact of different GrIS evolutions. In contrast and by design of the experiments, the total ensemble range is substantially larger, and determined by the three ocean setups of low, intermediate, or high AMOC tipping thresholds. These ensemble model runs thus highlight that uncertainties in these two Earth system components do not amplify each other, largely due to the mutual stabilizing feedback between them, which is a robust feature in the Bern3D model for a large range of perturbed parameters.

3.4. Preventing GrIS tipping by rapid CO_2 reductions

Rapid reduction of CO_2 concentrations to pre-industrial levels may prevent the crossing of major tipping points (figure 6, Ritchie *et al* [53]). Our findings indicate that a ramp-down either after 100 or even 500 years of stabilized 2×CO_2 allows the GrIS to stabilize above the tipping point, regardless of ice-sheet parameter uncertainties at least within the simulated timeframe of 3000 years. For the 4×CO_2 scenarios, a rapid reversal after 100 years is still sufficient to either prevent GrIS tipping entirely for most ensemble members, or to slow down its decay such that it would take tens of thousands of years to vanish. In contrast, 500 years of stabilized 4×CO_2 followed by a ramp-down to pre-industrial levels allows for a substantial fraction of up 40% of GrIS to melt. Although the ice-sheet starts to slowly grow again for nine out of ten ensemble members after pre-industrial CO_2 conditions are reached again, it cannot be excluded that a runaway disintegration is irreversible at this point. This can also be understood from the GrIS hysteresis (figure 2), which outlines the mono- and bistable regimes, suggesting that two ensemble members are bistable under pre-industrial CO_2 concentrations.

The full AMOC recovery strongly depends on the timing of ramp-down due to the thermal response, but also meltwater fluxes change dramatically during this time. During the CO_2 ramp-down, the AMOC rapidly increases, overshoots its

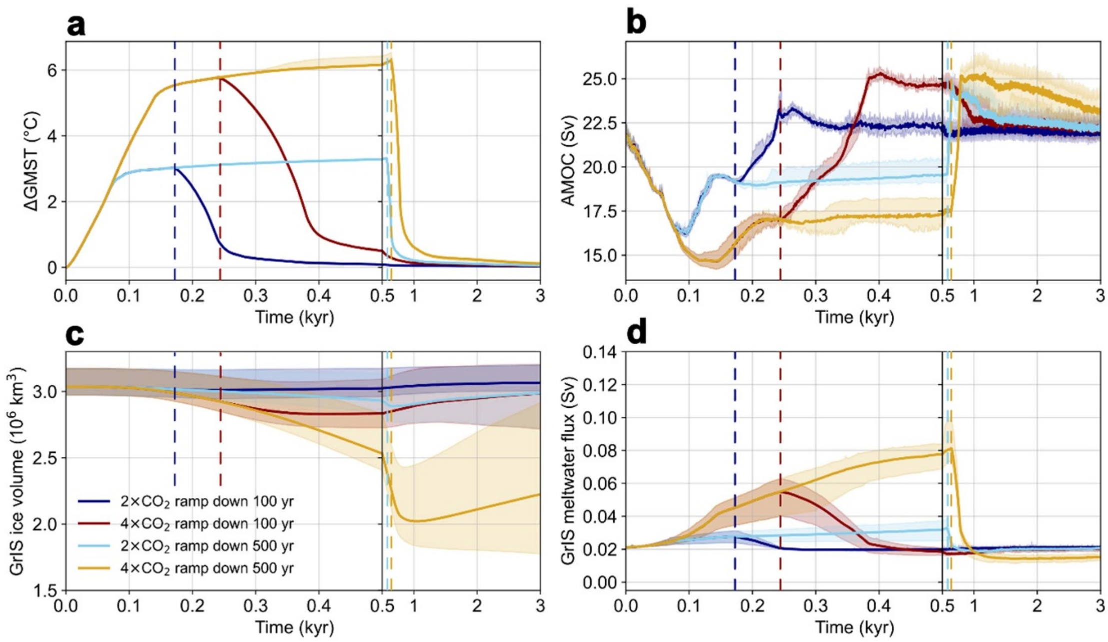

Figure 6. Rapid emissions reduction scenarios. Timeseries ensembles for experiments following 1%/yr 2 × CO_2 (blueish colors) and 1%/yr 4 × CO_2 (red and yellow) of (a) GMST, (b) AMOC, (c) GrIS ice volume, (d) and total GrIS meltwater flux, but with ramp downs of the CO_2 concentrations back to pre-industrial levels after 100 yrs (darker colors) and 500 yrs (lighter colors) of stabilization. Shadings indicate ensemble range, while thick lines are the ensemble mean. Dashed lines depict start of ramp-down of CO_2 concentrations.

pre-industrial strength by up to 3 Sv, and then slowly returns to its steady-state (figure 6(b)).

These results underscore that the most effective measure to prevent tipping points to be crossed is (1) limit warming, and (2) a rapid reduction in atmospheric CO_2 concentrations [54]. Although the GrIS, due to its large inertia, might allow more time before CO_2 concentrations need to be reduced, this is likely not true for other Earth system components that also exhibit tipping behavior and might approach irreversible change much sooner.

4. Conclusions

Every additional increment of anthropogenic warming elevates the risk of crossing tipping points in critical Earth system components [1, 5]. We here provide an assessment of potential cascading interactions between the GrIS and the AMOC using the Bern3D model of intermediate complexity. As warming intensifies, the AMOC weakens primarily due to thermal effects on deep convection [55], raising concerns that increasing meltwater fluxes from the disintegrating GrIS may trigger a full AMOC collapse [56]. Our findings suggest that this sequence of events is unlikely under a middle-of-the-road scenario (i.e. 2×CO_2,, corresponding to about 3 °C warming after 200 years), but becomes increasingly probable for higher emission scenarios. A key factor contributing to this more stable behavior is the delayed response of the GrIS to the warming, which results in maximum meltwater fluxes occurring only after hundreds of years, when the AMOC is already in its recovery phase. This asynchrony diminishes with stronger warming levels, thereby increasing the likelihood of an AMOC collapse. Yet, even maximum meltwater fluxes remain substantially smaller than typically applied fluxes in hosing experiments [47]. A stabilizing factor in the coupled system is the effect of the strongly reduced northward heat transport, even under high-emission scenarios. The cooling induced by a weakened AMOC reduces GrIS meltwater fluxes, preventing further reduction in circulation strength due to the meltwater feedback. Moreover, in the Bern3D model the North Atlantic cooling increases non-linearly with decreasing AMOC strength, causing GrIS meltwater fluxes to diminish as the AMOC approaches its tipping point, further stabilizing the system before tipping points are crossed. Nevertheless, this stabilization only concerns the meltwater feedback, and it cannot be excluded that the AMOC may transition into a collapsed state solely due to thermal forcing and its impact on the hydrological cycle. In such a case, the cooling from the reduced northward ocean heat flux may prevent any substantial disintegration of the GrIS, provided warming levels remain below 3 °C. For a more robust assessment, reducing biases in the AMOC's stability conditions in Earth system models is crucially important. Yet, the comparison to results from the AWI-ESM, which is a more complex and higher resolved model also with dynamic ice-sheets, shows essentially the same response as found here [6], suggesting that the Bern3D intermediate complexity models describes the fundamental dynamics well. The tipping of the GrIS (and the AMOC) may also be prevented if CO_2 concentrations are returned to lower levels quickly enough. To minimize the risk of practically irreversible state transitions of the AMOC or the GrIS, it is thus imperative to limit maximum CO_2 concentrations and return them to pre-industrial levels as rapidly as possible.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5281/zenodo.15599820. Data will be available from 04 August 2025.

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Author contributions

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Conceptualization (lead), Funding acquisition (equal), Investigation (lead), Methodology (lead), Visualization (lead), Writing – original draft (lead)

Thomas F Stocker
Conceptualization (supporting), Resources (supporting), Writing – review & editing (supporting)

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