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ABSTRACT

The Atlantic Meridional Overturning Circulation (AMOC) stability landscape is commonly investigated with single-realization hysteresis diagrams driven by freshwater input in the North Atlantic Ocean. However, the effect of CO₂ forcing on one side and the role of internal climate variability on the timing of tipping and the AMOC hysteresis on the other side remain less explored. Here, we address this gap by running three independent AMOC hysteresis simulations, consisting of a slow ramp-up plus ramp-down in the CO₂ concentration (0.2 ppm/year) within the PlaSim-Large-Scale Geostrophic (LSG) intermediate complexity model. We show that the realizations of the CO₂-driven hysteresis cycle, and particularly, the timing of the tipping and recovery, are remarkably affected by internal climate variability. In one of the three simulations, we even observe a reversed cycle, where the AMOC recovers at a higher CO₂ level than at the collapse point. While statistical Early Warning Signals (EWSs) show some success in detecting the tipping points, we also find that the internal variability in the EWS considerably reduces the predictability of collapse and leads to false positives of an approaching AMOC tipping. We suggest that the AMOC collapse in the presence of internal climate variability may have characteristics that deviate substantially from the behavior seen in simple models and that caution is needed when interpreting results from a single-experiment realization. Our findings highlight the need for a probabilistic approach in defining a “safe operating space” for AMOC stability, since it might not be possible to define a single critical CO₂ threshold to prevent AMOC collapse.

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The Atlantic Meridional Overturning Circulation (AMOC) is a system of oceanic currents in the North Atlantic, which is vulnerable to pronounced disruption due to anthropogenic climate change. These disruptions, often referred to in climate science as “tipping points,” could lead to dramatic consequences, particularly for regional climates. Current future climate projections suggest that the AMOC will weaken as a result of rising atmospheric CO₂ levels, but there is considerable uncertainty about the timing and severity of such changes. Climate models disagree on when or at what level of CO₂ concentration an AMOC collapse might occur, with some suggesting the possibility of a weakening followed by recovery rather than a complete collapse. A key source of uncertainty arises from the climate system’s internal variability. In this study, we run three independent simulations

with identical external greenhouse forcing in an intermediate complexity atmosphere–ocean coupled climate model to quantify the role of internal climate variability. The simulations show remarkable differences in the timing of tipping points and the coexistence of an AMOC active and collapsed state for a large range of CO₂ values. We suggest that the climate internal variability can potentially have a non-negligible role in the occurrence of AMOC tipping points under future climate change.

INTRODUCTION

The Atlantic Meridional Overturning Circulation (AMOC) represents the regional branch of the global oceanic thermohaline

circulation. It is a key oceanic current system in the Atlantic Basin, moving surface warm, salty water northward and deep, cold water southward.¹ Since the early 60s, the AMOC has been considered a system able to manifest multistability,² although it is not clear whether under present climate conditions, it is in a multistable or monostable regime.¹ Paleoclimate studies link AMOC changes to abrupt climate transitions, such as Dansgaard–Oeschger events.^{3,4} Anthropogenic climate change is expected to weaken the AMOC by reducing surface water density, particularly via surface warming and freshwater input from ice-sheet melting, thus suppressing North Atlantic oceanic convection and deep water formation.^{5,6}

Numerical models show that variations in the AMOC strength can lead to widespread climate impacts^{7–9} so that the AMOC is considered one of the most relevant tipping elements in the climate system.¹⁰ Indeed, major concern lies in the possibility that the AMOC may undergo a collapse under anthropogenic climate change, resulting in a significantly weakened state. Although an AMOC collapse is considered a low-probability event for this century,⁵ models have shown that the AMOC collapse can occur in response to external forces like freshwater forcing (FWF) or greenhouse gases increase.^{1,11–14} Early Warning Signals (EWSs) for tipping points applied to observational and model data suggest that the current AMOC state may be close to losing stability.^{14–16} Further concerns arise from the fact that the current generation of climate models may overestimate AMOC stability due to biases in the simulation of the freshwater balance of the North Atlantic Ocean.^{1,15} Overall, while an AMOC collapse is possible, the likelihood of reaching a critical threshold, i.e., a threshold value in some climate variable beyond which the system is destabilized, remains highly uncertain.

Under conditions when the AMOC is in a multistable regime, collapses can be triggered also by internal chaotic variability, known as noise-induced transition.^{5,17} While AMOC collapses driven by an external forcing have been extensively examined (bifurcation transitions or rate-induced transitions⁵), the possibility of noise-induced transitions and the role of internal climate variability in triggering a collapse have been less systematically explored,^{18–20} especially with complex climate models. Recently, it has been shown that in one state-of-the-art climate model, projections under the SSP2-4.5 scenario may evolve into either an AMOC collapse or recovery solely because of internal variability.¹⁹ In Cini *et al.*,²⁰ using an intermediate complexity coupled climate model [PlaSim-Large-Scale Geostrophic (LSG)], we assessed the possibility of AMOC collapses in stationary climate conditions driven by the internal climate variability.^{5,17} The model did not show AMOC spontaneous collapses at 354 ppm of CO₂ in a 2500-year control simulation. Nonetheless, we could successfully explore the multistability of the model by employing a rare event algorithm.^{21–24} This technique allows to sample, more efficiently than control or ensemble simulations, model trajectories leading to persistent negative anomalies in the AMOC. The technique consists in operating a genealogical algorithm on top of an ensemble simulation, in which members whose trajectories have a weak AMOC are cloned, while those with a strong AMOC are killed along the simulation. This gradually shifts the ensemble towards weaker AMOC values, eventually triggering its collapse.

Here, following the PlaSim-LSG setup used in Cini *et al.*,²⁰ we explore the possibility of reaching the collapsed AMOC state via increased CO₂ forcing and whether internal climate variability remains important in setting the tipping event. While noise-induced transitions may be extremely rare if the system is far from a bifurcation tipping point, they are expected to become less and less rare the closer the system gets to the critical threshold. It is, therefore, of great interest to study the role of internal climate variability in triggering AMOC tipping under increased CO₂ forcing. To best identify the presence of tipping points, we explore the AMOC evolution in a small (three members) ensemble of so-called *hysteresis experiments*,²⁵ i.e., simulations with a very slow ramp-up and ramp-down in the external forcing designed to reveal the hysteresis behavior of the AMOC. If the forcing varies sufficiently slowly that the system remains in quasi-equilibrium conditions, the resulting hysteresis diagrams can provide insight into the location of the system's bifurcation tipping points. AMOC hysteresis experiments have been mostly performed under FWF,²⁶ as in the recent work by van Westen and Dijkstra,²⁷ while CO₂ forcing is less explored.^{28–30} FWF mimics the impact of surface salinity reduction in the North Atlantic due to the Greenland ice-sheet melting, but under future projections, AMOC weakening is strongly impacted also by atmospheric warming.³¹ It is worth noting that the PlaSim-LSG model does not include a representation of the Greenland ice-sheet, meaning that any AMOC weakening in the model occurs due to other mechanisms. Moreover, assessing the AMOC hysteresis cycle with a small ensemble of coupled climate model simulations is particularly novel, since, to our knowledge, previous similar studies were based on a single ensemble member. This allows a clean exploration of the role of climate internal variability during bifurcation-induced transitions by comparing the different ensemble members' evolutions.

We note that hysteresis experiments are highly dependent on the rate of the forcing so that results can differ qualitatively, even for simulation assumed in quasi-equilibrium conditions.^{28,29} It is, indeed, established that the rate of the forcing also has an influence on the occurrence of tipping points.¹⁷ Here, we propose simulations with a CO₂ increase of 0.2 ppm/year, which is an order degree smaller than the current anthropogenic one. The value is close to the case of Gérard and Crucifix²⁸ (0.14 ppm/year), while an even weaker rate (0.005 ppm/year) was used in Willeit and Ganopolski.²⁹ We note that ramp-up and ramp-down experiments with a faster rate of CO₂ change have been explored using several state-of-the-art models.^{32–37} However, only a small subset of these experiments reached a weak AMOC stable state after a ramp-up and eventual stabilization period,^{33–37} which reflects the remarkable model dependency of the AMOC stability landscape. At the same time, these studies are conceptually different from quasi-equilibrium hysteresis experiments and, as it will be suggested in this paper, a stabilized climate and long enough timescales may be important ingredients to trigger an AMOC tipping.

The structure of the paper is as follows. The section titled Methods introduces the PlaSim-LSG climate model, the experimental design, and the statistical analysis performed on the data. In the section titled Results, we present the ensemble hysteresis experiment and provide additional evidence supporting the influential role of internal climate variability in triggering an AMOC tipping point.

Then, we assess whether these tipping events could have been anticipated using the EWS,¹⁵ which is crucial for assessing the reliability of these indicators in anticipating a tipping point. The section titled Conclusions offers an interpretation of these results in the context of recent studies.

METHODS

PlaSim-LSG coupled climate model

We perform the simulations using an Earth system Model of Intermediate Complexity,³⁸ specifically the Planet Simulator (PlaSim) General Circulation Model (GCM),^{39,40} coupled with the Large-Scale Geostrophic (LSG) Ocean model.^{41,42} Various configurations of PlaSim-LSG have been used for different studies from paleoclimatic to future climate projections.^{43–45} Recently, it has been used in studies focused on the AMOC,^{20,46} thanks to a convenient balance between computational efficiency and a reasonably realistic representation of key climate mechanisms, especially in the Northern Hemisphere.⁴⁷ It is particularly suitable for studies of extreme events requiring large ensemble simulations.^{20,21,47}

PlaSim is based on the wet primitive equations, representing the conservation of momentum, mass, moisture, heat, and the equation of state. It uses the hydrostatic approximation. PlaSim includes parameterizations for sea ice, land processes, and a slab ocean model. The slab ocean functions as a thermal and freshwater reservoir, interacting with the LSG model. LSG, on the other hand, is a simplified ocean model that represents ocean geostrophic dynamics on spatial scales larger than the internal Rossby radius and on time scales longer than those associated with typical periods of gravity modes and barotropic Rossby wave modes. It implicitly solves the primitive equations, neglecting the nonlinear terms of the Navier–Stokes equation. Interaction between PlaSim and LSG occurs via the PlaSim slab ocean layer (50 m), which provides 10-day average temperatures to be used as the uppermost layer for LSG. Similarly, 10-day average momentum and freshwater fluxes from the sea ice and atmospheric modules are passed to LSG. Conversely, the PlaSim slab ocean is forced to relax toward the LSG uppermost layer during the subsequent 10 days of PlaSim evolution.^{43,44} Ice-sheets are prescribed as other land points but with surface and soil properties appropriate for ice. This implies that the model does not account for the North Atlantic surface freshening associated with Greenland ice-sheet melting and that the model lacks a mechanism of destabilization of the AMOC present-condition state.

The model was run with the same model configuration as in Cini *et al.*,²⁰ first proposed in Angeloni^{44,48} in particular for what concerns the parameterization of the ocean vertical diffusivity. Under these conditions, the AMOC exhibits a stable behavior over the millennial time scale ranging from 17 to 21 Sv and shows oscillation across different time scales, up to the multicentennial scale.⁴⁶ PlaSim operates at a T21 horizontal spectral resolution with 10 vertical levels in the atmosphere, while LSG has a nominal 3.5° horizontal resolution with 22 vertical levels in the ocean. Greenhouse gases are represented by a fixed CO₂-equivalent concentration.

The hysteresis experiment is performed with a slow increase in CO₂-equivalent concentration (ramp-up, 3000 years at 0.2 ppm/year) followed by a symmetric decrease (ramp-down, 3000 years at −0.2 ppm/year). The simulations are initialized at the end of a

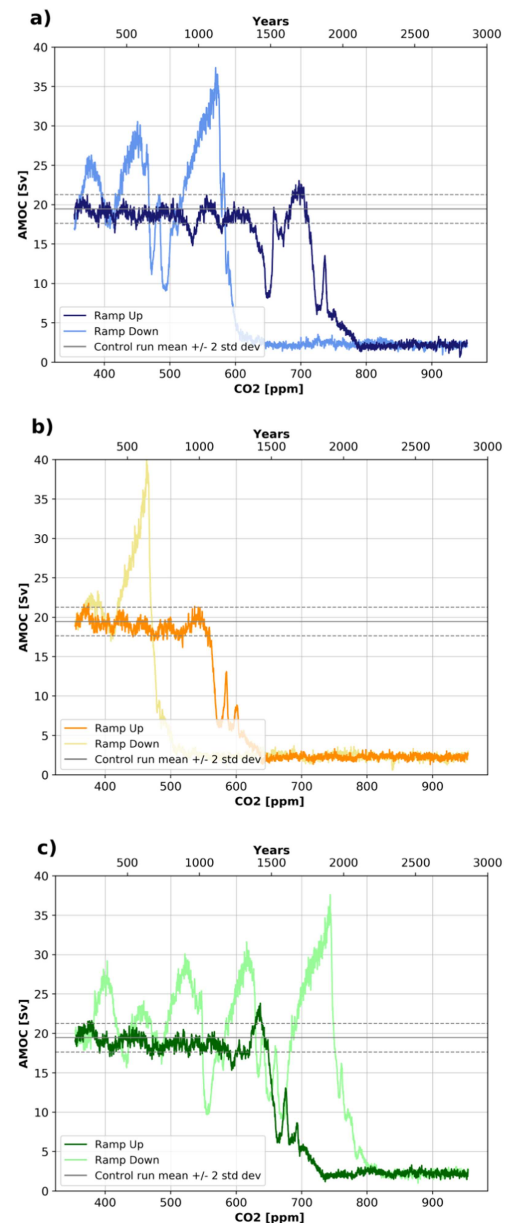


FIG. 1. AMOC hysteresis in three independent 6000-year simulations (a)–(c). Ramp-up experiments (dark colors) represent AMOC 3000-year evolutions with CO₂ linearly increasing from 354 to 954 ppm, while ramp-down (light colors) represents the AMOC evolution with CO₂ linearly recovering at 354 from 954 ppm. The dashed gray lines delimit the AMOC typical variability (mean, ± 2 standard deviation) in a 2000-year control run simulation at 354 ppm.

2000-year control run. Two members [blue and yellow in Figs. 1(a) and 1(b)] start from the same initial condition with the only addition of a small random noise perturbation in the Sea Level Pressure (SLP). The third member [green, Fig. 1(c)] is initialized 8 years earlier in the control run, implying that the initial ocean state is

also different. The PlaSim-LSG control run is performed as a single member simulation over 2000 years at 354 ppm.^{20,44,48}

AMOC metric

The North Atlantic meridional overturning streamfunction B2465614 at latitude θ and depth z is defined as

$$\Psi_{\theta}(z) = - \int_{\varphi_{west}}^{\varphi_{east}} \int_{z_{bottom}}^z v_v r_T |\cos\theta| d\varphi dz', \quad (1)$$

where Z_{bottom} represents the oceanic depth v_v is the meridional velocity, φ is the longitude angle and r_T is the Earth radius, φ_{east} and φ_{west} represent, respectively, the east and west margin of the Atlantic Ocean basin at latitude θ . The AMOC strength is obtained as the maximum of the $\Psi_{\theta}(z)$ between 46° and 66°N and below 700 m,

$$AMOC = \max_{z,\theta} \{ \Psi_{\theta}(z) \} V_{z>700\text{ m},46^{\circ}-66^{\circ}\text{N}}. \quad (2)$$

The AMOC strength is calculated at each ocean model time step (every 10 days) and averaged to obtain an annual mean AMOC index.

Early warning signals

Early Warning Signals (EWSs) are statistical indicators that are often used in the climate literature to try to anticipate the occurrence of a tipping event for systems (possibly) approaching a tipping point due to the changes in a parameter.^{14–16} In this study, we test two EWSs commonly used in the literature: the variance and the *restoring rate* EWS, following the definition given in Boers.¹⁵ They are based on the fact that, for a system approaching a bifurcation-induced tipping, critical transitions are typically preceded by changes in some intrinsic properties of the system due to a weakening of the internal feedback stabilizing the system. Thus, the detection of an increasing trend in the variance, for instance, may be considered a warning that the system is losing stability.

Both the variance and the restoring rates are computed within Y -year long sliding windows of the AMOC index, with Y equal to 70-year (as in Boers¹⁵) or 300 years (to better capture low frequency variations in the ocean). Within each window, the time series is first linearly detrended before computing the two statistics. In particular, the restoring rate is then defined as the linear regression coefficient between the tendency in x and the detrended value of X ($\frac{dx}{dt} = \lambda x + \eta$). As long as λ is negative the system tends to restore toward its equilibrium state. However, as λ approaches zero, the system becomes less stable and oscillations in the AMOC may take a longer time to recover. Compared to the variance, Boers,¹⁵ showed that the restoring rate is less affected by changes in the autocorrelation of the external noise, i.e., atmospheric variability acting on the surface ocean so that λ is a better measure of the internal properties of the system.

RESULTS

Hysteresis cycle

Results of the hysteresis experiment are presented in Fig. 1. Gray dashed lines in Fig. 1 represent the typical AMOC variability

in the control run. Notably, the three simulations start from close initial conditions (see Methods), thus any difference in the AMOC evolution is only due to the internal climate variability generated by the model. The ramp-up (dark colors) represents the experimental branch in which CO_2 gradually increases at a rate of 0.2 ppm/year, from 354 to 954 ppm. Conversely, the ramp-down (lighter colors) is initiated in the final year of the ramp-up and follows a reversed trajectory, with CO_2 decreasing at the same rate.

All three experiments show an overall similar AMOC evolution, which is characterized by an AMOC collapse to less than 5 Sv in the ramp-up experiment, and an AMOC recovery in the ramp-down simulation. However, striking differences can be noted between the three experiments. First, the tipping in the ramp-up occurs at different CO_2 levels, within the 550–700 ppm range, and hence a difference up to 150 ppm (equivalent to more than 750 years) between the earliest and latest tipping. Furthermore, the range in the timing of the tipping point of the ramp-down, i.e., when the AMOC recovers from the off to the on states, is even larger, reaching up to 300 ppm (or approximately 1500 years). Expressed in terms of global warming, the AMOC tipping point shown in Fig. 1(c) corresponds to a global-mean temperature anomaly of approximately 3.5°C above the control run [Fig. S3(a) in the supplementary material].

An even more striking difference between the simulations regards the landscape of the hysteresis cycle. The blue and orange simulations exhibit a typical AMOC hysteresis, in which the AMOC remains in the collapsed state during the ramp-down experiment up to a forcing strength notably lower than the value at which it had collapsed.^{26–28,30} In contrast, the green simulation shows a “reversed cycle,” i.e., the AMOC collapses between 650 and 700 ppm but recovers at higher concentration, around 750 ppm. We are not aware that this behavior has been shown in the context of AMOC hysteresis experiments.

These results are a strong indication of the remarkable role in internal climate variability that is so influential that it can potentially reverse the characteristic cycle shaped by the bifurcation tipplings. The conventional interpretation of the AMOC hysteresis cycle suggests that there are deterministic shifts between AMOC-on and -off states at given thresholds in an external forcing parameter (here CO_2). However, these results suggest that the AMOC is instead in a bistable regime and that the occurrence of transitions between the two states must be interpreted probabilistically. Indeed, Cini *et al.* showed that the model in this configuration already has two stable AMOC states at 354 ppm (namely, a modern-like AMOC-on state and the AMOC off state).²⁰ Transitions between the states only driven by the internal climatic variability exist, i.e., for example, there is always a probability different from zero that the AMOC may spontaneously collapse without any external forcing. These new results suggest that the CO_2 concentration mainly acts by influencing the transition probability between the two states. The reversed cycle, therefore, emerges mainly as a stochastic phenomenon.

In two out of three simulations [blue and green solid lines in Figs. 1(a)–1(c)], the AMOC collapse in the ramp-up is preceded by an unprecedented positive anomaly compared to the control run values. This suggests a behavior that is more complex than a gradual AMOC decline evolving into the collapse of the circulation. In the case of the blue solid lines in Fig. 1(a), the behavior is particularly

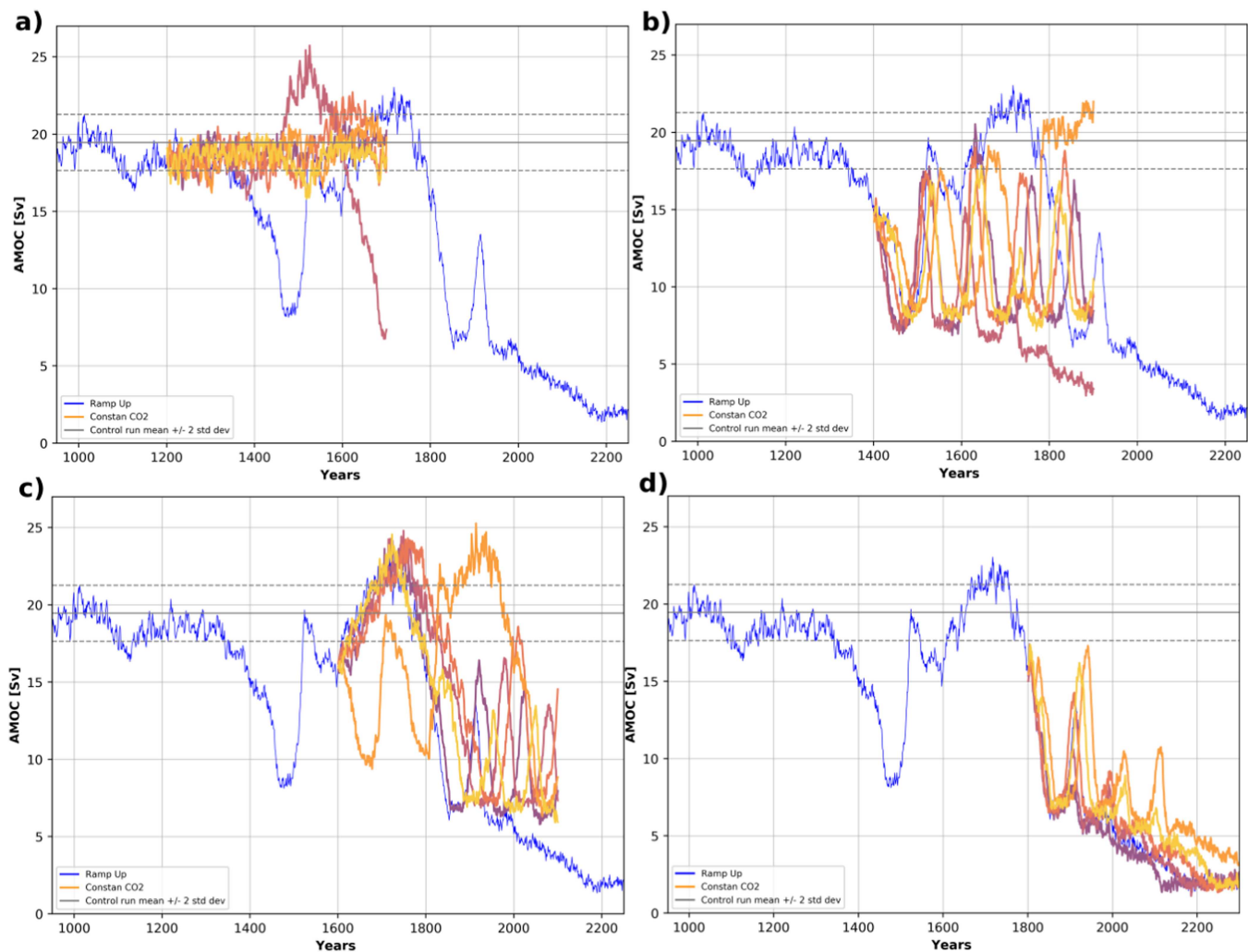


FIG. 2. AMOC internal variability while approaching the tipping point. The simulations branch the solid blue line of Fig. 1 at four different points, respectively, at 594 (a), 634 (b), 674 (c) and 714 ppm (d). Each ensemble simulation is performed at constant CO₂ concentration. The five members of the same simulation differentiate only for a small initial perturbation of surface pressure. The gray lines represent the AMOC range during the 2000-year control run at 354 ppm.

complex: the AMOC shows a dramatic decrease at about 650 ppm, followed by bouncing to an AMOC positive anomaly. Such a strong oscillation may be interpreted as a *failed attempt* of the model to transition to the AMOC-off state, since the other experiments show that collapses to the off states are already likely at that greenhouse forcing level.

Despite these differences, there are also some mechanisms that are shared between the three simulations. During the AMOC abrupt decrease, which lasts nearly 500 years, the circulation strength shows two relative maximum peaks. While this could be considered as an intrinsic property of the model, this behavior was also pointed out in Gérard and Crucifix²⁸ using a different intermediate complexity model. Likewise, during the ramp-down, the recovery of the AMOC is always characterized by an overshoot. This behavior has

also been observed in previous studies,^{28–30} even employing fresh-water forcing.^{26,27} In our case the overshoots are also followed by a damped-oscillator-like behavior, with such fluctuations persisting for more than 1000 years.

Internal variability

To better illustrate the role of internal variability in the transition between the AMOC-on and -off states, a second set of experiments is conducted. The blue ramp-up simulation (blue solid line in Fig. 1) is branched in four different points, prior to the AMOC collapse, at CO₂ values of 594, 634, 674, and 714 ppm. From each point, a new five-member ensemble is initiated by adding small random SLP perturbation, and keeping the CO₂ concentration fixed at the

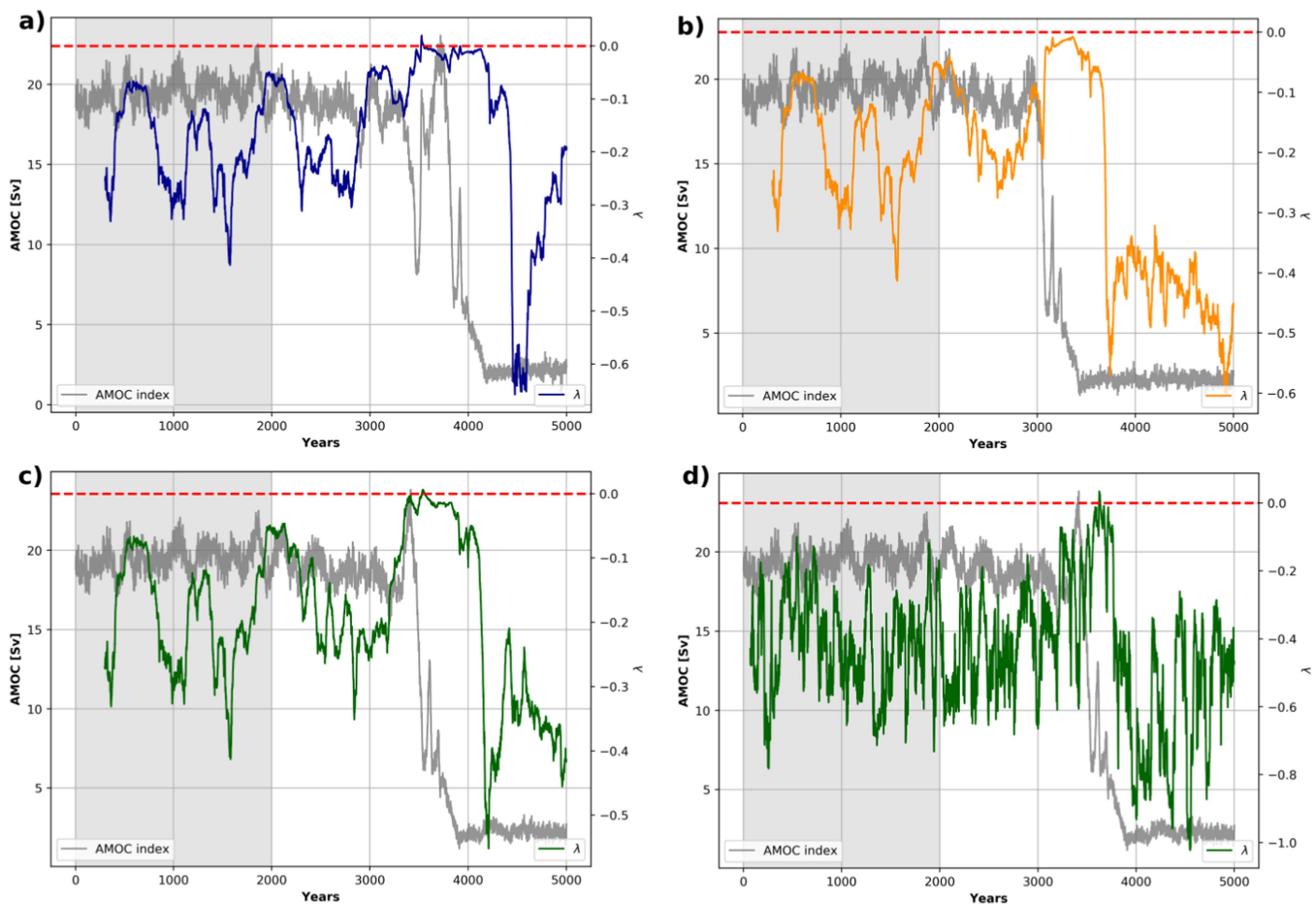


FIG. 3. EWS for the AMOC collapse. The gray solid lines represent the AMOC time series during the control run experiment (first 2000 years) plus the ramp-up experiments (Fig. 1). (a)–(c) In green, evolution of the restoring rate λ with a backward 300 year window and (d) as in (c) but with a 70 year window. The red dashed line represents the zero in the restoring rate when the evolution of LAMBDA crosses this line; the system loses stability.

branching value. This enables us to explore the characteristics of internal variability at stationary forcing in different proximities of the tipping point.

Results are presented in Fig. 2. The five ensemble members show that in the first three simulations at least one member evolves markedly differently from the others. Notably, in the range between 594 and 674 ppm [Figs. 2(a) and 2(b)], simulations started at the same point diverge toward different AMOC states, i.e., it is clearly visible a member evolving to the collapsed state. Finally, all members initiated at 714 ppm, i.e., year 1800 [Fig. 2(d)], converge to the AMOC off-state, indicating that the bifurcation tipping point has been passed. Of particular interest are the two ensembles initiated in the years 1400 and 1600 [Figs. 2(b) and 2(c)], where some members exhibit intriguing oscillatory cycles, resembling quasi-stable limit cycles which would be consistent with the passing of a subcritical Hopf bifurcation.^{49,50} In a recent study performed with the same model,

it was also shown that the edge-state of the AMOC, also featured an oscillatory behavior⁵¹ which is presumably consistent with our finding.

To further support these results, Supplementary Figs. S1 and S2 in the [supplementary material](#) show different experiments consisting of a large 50-member ensemble simulations. The experiments are initiated from the same initial condition as the blue and orange members, but with a faster CO₂ increase (from 2 to 12 ppm/year) for 125 years. First, they suggest that a long stabilization period (100–120 years) is needed in order to observe an AMOC collapse, even for extremely high CO₂ concentrations (above 1000 ppm). Moreover, the weakest simulation (2 ppm/year), followed by a stabilization period of 275 years with CO₂ fixed at 604 ppm (Fig. S2 in the [supplementary material](#)) shows that almost half of the members relax to the collapsed state while others recover to initial AMOC values or show oscillatory behaviors. This confirms the presence of an edge-state in whose proximity the AMOC can either evolve toward

an AMOC-on or AMOC-off state solely due to internal climate variability.

Early warning signals

We finally test two statistical EWSs proposed in the study by Boers.¹⁵ These indicators are designed to provide a warning if the system is approaching a bifurcation-induced transition, by identifying the changes in the statistics of the internal variability of the system. However, in our case, the tipping event involves a complex interplay between a bifurcation-induced transition and noise-induced tipping, meaning that internal climate variability contributes to the occurrence of the tipping event itself. Therefore, it is valuable to assess whether the indicator may provide advanced warning in this type of scenario.

Figures 3(a)–3(c) show the evolution of the restoring rate for a 300-year long sliding window for the three AMOC collapses presented in Fig. 1. The AMOC signal inside each window is detrended before computing the EWS. The variance indicator is reported, with similar results, in Fig. S4 in the [supplementary material](#). The first 2000 years in Fig. 3 refer to the control run experiment, when the system is in a stationary state. In each simulation, the indicator correctly tends to zero when the tipping point is approaching. However, at the same point, it seems useless in predicting the collapse years in advance. Specifically, we observe two key issues affecting the reliability of these indicators. First, especially in the case of the variance (Fig. S4 in the [supplementary material](#)), the critical increasing trend preceding the tipping point is evident only in close proximity to the event itself. The predictability of the collapse, thus, vanishes since no useful information can be extrapolated more than by the direct observation of the AMOC index trend. Second, the indicators seem to be deeply affected by the AMOC internal variability, which exhibits coherent oscillation on different time scales. This means that interpreting an increasing trend of the indicator as a forthcoming collapse may produce multiple false positive warnings. Indeed, rapid increasing trends are found multiple times even during the control run experiment [Figs. 3(a)–3(c)]. These trends are highly significant when analyzed applying the Mann–Kendall test as suggested by Boers¹⁵ (Fig. S5 in the [supplementary material](#)). Attempts to disentangle oscillations due to internal climate variability from those associated with the “critical slowing down”⁵² by applying a high-pass filter fail, as there is no clear evidence of a distinct separation of scales between the two (Fig. S6 in the [supplementary material](#)). Furthermore, Fig. 3(d) reproduces the same data of Fig. 3(c) but with a 70-year window, i.e., the one used in Boers.¹⁵ Contrary to Boers,¹⁵ we report that varying the window length affects the results [Figs. 3(c) and 3(d)]. A narrower window typically produces a noisier signal and delays the occurrence of the alarm. The deficiencies observed in the EWS suggest that the characteristics of “critical slowing down” may differ in this case. Critical slowing down EWSs are based on assumptions on the nature of the bifurcation and of the internal variability (assumed as noise) of the dynamics. Our results show that in an actually observed, global warming induced collapse of the AMOC, both aspects can substantially deviate from those assumptions. The observed oscillations in proximity to the tipping [see Fig. 2(b)] are reminiscent of Hopf bifurcation already present in simple models of the AMOC,⁴⁹ and the properties of the internal

variability seem more complex than what is assumed in the EWS theory. Both factors could account for the issues affecting EWSs in our experiments and suggest carefulness when applying these indicators to observational data.

CONCLUSIONS

We run a small ensemble simulation (three members) of the PlaSim-LSG model aimed at identifying the presence of hysteresis in the AMOC response to external forcing. The simulation consists in a quasi-equilibrium transformation of the model attractor in response to slow changes in the CO₂ atmospheric concentration (0.2 ppm/year). The model shows in all three ensemble members an AMOC collapse during the CO₂ ramp-up to 954 ppm and an AMOC recovery during CO₂ ramp-down. At the same time, the presence of climate internal variability substantially alters the timing of the AMOC tipping events, in both the AMOC collapse and its recovery. This introduces an uncertainty ranging from approximately 150 ppm (750 years) for the collapse to 300 ppm (1500 years) for the recovery and a reversal of the hysteresis cycle in one of the three members. In this model, the hysteresis cycle displays complex behavior like large oscillations and positive AMOC anomalies prior to the tipping events. While previous studies have typically explored hysteresis with single realizations, our results highlight the value of using ensemble simulations, even with a small number of ensemble members. Additionally, in simplified models, the AMOC shows little to no internal variability on decadal to centennial timescales, leading to the repeated simulations of the AMOC hysteresis diagram that often closely overlap. This lack of variability should be viewed as a limitation, indicating that these models may miss important processes, which could be critical in real-world scenarios.^{28,29} Concerning experiments with faster increases, such as Representative Concentration Pathways (RCP) scenarios, our findings in Figs. S1 and S2 in the [supplementary material](#) indicate that, at least in our model, a long stabilization period (100–120 years) appears essential to tip into a different stable state.

The emerging role of internal climate variability and noise-induced tipping in experiments with different levels of model complexity^{18–20} suggests an intrinsic limitation to the predictability of the AMOC tipping point. In fact, five-member simulations that differ only for perturbations in the atmospheric condition may evolve to different AMOC states [Figs. 2(a) and 2(b)]. These results are consistent with Romanou *et al.*,¹⁹ who reported the occurrence of an AMOC divergent behavior in an ensemble simulation conducted with the GISS climate model under the SSP2-4.5 scenario. They also support the results of Mehling *et al.*⁵³ who, using a conceptual climate model, suggested that the predictability of the final asymptotic AMOC value can vanish because of the presence of fractal basin boundaries between the two AMOC states, and, hence, a strong sensitivity to initial conditions. This highlights the necessity of employing a probabilistic framework to define a “safe operating space” for the AMOC stability, rather than relying on a single critical CO₂ threshold, since uncertainties and internal variability are intrinsically embedded in the system.

Our results show that in systems where internal variability has a non-negligible influence on the occurrence of the AMOC tipping points, EWSs appear to have limited predictive skills. In particular,

the AMOC internal variability, that exhibits coherent oscillations across different time scales, can mask the trend in the early warning indicator due to an approaching tipping point and generate false positives if used in a predictive sense. The attempts to disentangle oscillations due to internal climate variability from those associated with the “critical slowing down” fail. At the same time, we stress the fact that ensemble simulations at constant CO₂, initialized within the range of 534–674 ppm (Fig. 2), reveal divergent AMOC trajectories. This suggests that as the system approaches the bifurcation tipping point, the AMOC evolution variability is amplified, consistent with the theory behind statistical EWs. The ensemble divergent behavior is not expected to occur far from the tipping point.

Compared to van Westen and Dijkstra,²⁷ the tipping of the AMOC is neither achieved by the Greenland ice sheet melting nor by its representation via a freshwater forcing. This difference introduces a stabilizing bias for the AMOC-on state. Accounting for this mechanism would likely increase the probability of an AMOC collapse at lower CO₂ concentration values. While the hysteresis diagrams in Figs. 1(a) and 1(b) may suggest similarities with their result, we stress the fact that the physical mechanisms are different. In that FWF experiment, the AMOC-off state is associated with sea ice formation in the North Atlantic, which stabilizes the AMOC-off state and inhibits the AMOC recovery, since sea ice suppresses air–ocean heat fluxes. In contrast, the AMOC off-state obtained in our CO₂ forcing experiment is not associated with an increase in sea ice but with an overall Arctic warming. When the ramp-down phase begins, the sea ice is absent in the North Atlantic [see Fig. S3(b) in the supplementary material]. This might explain why our CO₂-induced AMOC-off state appears to be more prone to an AMOC recovery—including a reversed hysteresis—as the CO₂ concentration is reduced. This suggests it would be valuable to repeat similar CO₂-forced hysteresis cycles with state-of-the-art climate models.

SUPPLEMENTARY MATERIAL

See the [supplementary material](#) for the additional analysis.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Matteo Cini: Conceptualization (equal); Data curation (lead); Methodology (equal); Writing – original draft (lead). **Giuseppe Zappa:** Conceptualization (equal); Methodology (equal); Supervision (lead); Writing – review & editing (equal). **Francesco Ragone:** Conceptualization (equal); Methodology (equal); Writing – review & editing (equal). **Susanna Corti:** Conceptualization (equal); Funding acquisition (lead); Methodology (equal); Project administration (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are openly available in Zenodo, reference number 54.

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