

Reviewer #1

General comments

The manuscript explores the combined effect of changes in CO₂ concentrations and North Atlantic freshwater forcing on the existence of multiple AMOC modes in the fast climate model ClimberX. After plotting the AMOC intensity hysteresis cycles resulting from the two independent parameters and including discussions about the role of the initial AMOC state and the rate of change, Willeit and Ganopolski produced a stability landscape of the AMOC modes in the input space formed by the CO₂ concentrations and the freshwater forcing.

This work offers a new multidimensional approach to understanding AMOC stability in climate models. The stability landscape map is a convincing and comprehensive way to explore the domain of occurrence of AMOC mode shifts. The volume of simulations produced for this article is remarkable, and the experimental design allows advanced conclusions on the effect of AMOC mode shifts on the climate.

I have, nonetheless, major reservations about the clarity of the manuscript, as well as the justification of some arguments. The manuscript is, at times, difficult to read, and the description of the experiment and the calculations need to be revised to be able to evaluate the validity of the conclusions.

In summary, this paper is a strong contribution to the highly relevant question of AMOC manuscript in climate models. However, some work is required on the text to support the interpretations and conclusions. I recommend major revisions of the manuscript before publication in ESD. The main concerns I identified are the following.

We would like to thank the Reviewer for the detailed review of our paper. The raised comments will help to improve the clarity of the manuscript and are therefore gratefully acknowledged. We will address the Reviewers' comments as outlined below.

- The abstract is not reflective of the work and inconsistent with the conclusion, which is very clear. In particular, the abstract implies that the main aim of the paper is the impact of CO₂ concentrations on AMOC stability, instead of, as it is written in the conclusion, performing “a systematic analysis of the AMOC stability in the FWF–CO₂ space.”

We do not see any contradiction between the fact that in the paper we performed "a systematic analysis of the AMOC stability in the FWF-CO₂ space", while in the abstract we focused on the CO₂ dimension of this space. This is because the freshwater dimension of this phase space has already been studied in many previous studies, including ours. However, to focus the abstract a bit more on the AMOC stability landscape instead of the CO₂ response alone, we will add the following:

Generally, strong AMOC states are favored by high CO₂ concentrations and negative FWF, while weak AMOC states are characteristic for CO₂ levels below pre-industrial or positive FWF. Our AMOC stability landscape helps to explain AMOC instability in colder climates and provides useful context to interpret possible future AMOC trajectories in a warmer climate. In the absence of external FWF, e.g. from melting ice sheets, the model shows an increase in equilibrium AMOC strength with increasing CO₂ levels.

- In the introduction, the impact of CO₂ on the AMOC stability is said to “remain largely unexplored”, and the freshwater forcing outside of the 20-50°N band to be a rare occurrence. I believe both of these views are outdated, and the introduction is missing key references and discussion points that provide an accurate and comprehensive picture of the current state of the research. If these comments only concerned modern days, it should clearly be stated, and the results from the palaeo community should be discussed. I recommend splitting the second paragraph of the introduction into three parts. A first one on the CO₂ effect, including missing references (e.g. Brown and Galbraith 2016, Zhang 2017, Klockmann 2018, Vettoretti 2022), a second one on the FWF including missing references (e.g. Smith and Gregory 2009, Roche 2010, Kageyama 2013, Ivanovic 2018, Romé 2022) and a third one on the need for combined CO₂xFWF analysis and an introduction of your paper, which is currently too short.

We agree that the statement "remain largely unexplored" is indeed too strong. Some studies have already explored the AMOC response to CO₂, although they largely concentrate on the paleo-context. We will discuss that in the revised paper. We have already cited Brown and Galbraith (2016) and Klockmann et al. (2018) in our paper. At the same time, Zhang et al. (2017), Vettoretti et al. (2022) and the reviewer's own paper (Romé et al. 2022) are cited in another paper of ours which is devoted to Dansgaard-Oeschger events (Willeit et al., 2024, Climate of the Past Discussion). However, we think that these papers are not relevant to the present manuscript.

The cited FWF hysteresis experiments have all been performed with freshwater hosing between 20-50°N. We believe that transient water hosing experiments, that indeed focused also on different areas of the north Atlantic, are not relevant in the context of our paper.

The same applies to the second group of references suggested by the reviewer (Smith and Gregory 2009, etc...). They are all about transient water hosing experiments. We do not believe that there is a need to explain the fundamental difference between tracing the AMOC stability diagram and performing transient water hosing experiments. The number of papers describing such experiments, starting with the classical Manabe and Stouffer (1995) paper, is enormous and we cannot see any benefit for our paper and potential readers in citing these publications.

Altogether, we will rewrite the second part of the introduction with the following outline:

1. FWF hysteresis
2. CO₂ effect
3. Combined CO₂xFWF and introduction of our paper

as follows:

Stocker and Wright (1991) and Rahmstorf (1995) pioneered the use of surface freshwater forcing (FWF) experiments to analyze the stability of the AMOC and showed a hysteresis behavior in ocean models. Since then, models of different complexity have found that the AMOC shows a hysteresis behavior to FWF that is associated with multiple stable states (Ganopolski and Rahmstorf, 2001; Rahmstorf et al., 2005; Hawkins et al., 2011; Hu et al., 2012; van Westen and Dijkstra, 2023; Ando and Oka, 2021; Hofmann and Rahmstorf, 2009; Gregory et al., 2003; Lenton et al., 2009), although there is no consensus as to whether the AMOC is in a monostable or a bistable regime under present climate conditions (e.g. Weijer et al., 2019; Liu et al., 2017). While most of these hysteresis experiments have been performed under pre-industrial or present-day conditions, some have considered the

dependence on background climate by exploring the hysteresis behavior also for the last glacial maximum (Ganopolski and Rahmstorf, 2001; Schmittner et al., 2002; Ando and Oka, 2021; Pöppelmeier et al., 2021; Weber and Drijthout, 2007; Prange et al., 2002). Most of the hysteresis experiments have been performed with FWF in the latitudinal belt between 20–50°N in the Atlantic, thereby avoiding a direct perturbation of the convection sites further north in order to focus on the salt-advection feedback. FWF applied in the convection areas has a stronger impact on the AMOC (e.g. Ganopolski and Rahmstorf, 2001; Smith and Gregory, 2009), because the state of the AMOC is tightly linked to the production of deep water.

Convection and deep water formation do not only depend on surface freshwater flux, but are more generally controlled by the surface buoyancy flux, which also depends on the sensible heat cooling and the temperature at the sea surface. The temperature dependence of the surface buoyancy flux arises from the nonlinear equation of state of seawater, and in particular from the temperature dependence of the thermal expansion coefficient (Roquet et al., 2015). Perturbations to the climate will affect both the net surface freshwater flux, as a result of changes in the hydrological cycle, and the surface temperature, with intricate implications for AMOC stability. The effect of climate on AMOC stability has been investigated in relatively few studies, mainly by changing the concentration of atmospheric CO₂ (Brown and Galbraith, 2016; Klockmann et al., 2018; Galbraith and de Lavergne, 2019). These studies show a generally stronger AMOC in equilibrium with higher CO₂, but mostly focused on climates colder than present. Recently, Gérard and Crucifix (2024) have performed model simulations with slowly increasing and decreasing CO₂, producing an AMOC hysteresis in CO₂ space and suggesting an AMOC weakening in equilibrium with a warmer climate.

For an improved understanding of past and future AMOC evolution it is important to consider changes in climate and changes in the surface ocean freshwater balance due to changing land ice volume, since both are expected to play an important role for AMOC stability. Here we use an Earth system model to systematically explore the combined effect of surface FWF and climate on AMOC stability. The effect of external FWF is quantified by running experiments with FWF in different latitudinal belts in the North Atlantic, while the effect of climate is explored by varying the atmospheric CO₂ concentration, which is one of the main factors driving past and future climate changes.

- I do not believe that the authors can claim to be the first to attempt to draw a landscape of AMOC stability in the CO₂ x freshwater forcing space is true, see Brown and Galbraith 2016 for instance. However, I would say that this paper presents the most comprehensive and robust method up to date. If this claim only applies to modern-day studies of the AMOC, it needs to be clearly stated and put in context with palaeo studies.

To our knowledge we are the first who “have performed a systematic analysis of the AMOC stability in the FWF–CO₂ space”. Just to clarify the terminology: under stability (diagram) or phase portrait of the AMOC, we understand the 2D extension of the classical 1D Stommel’s hysteresis diagram, which depicts the strength of different possible, stable AMOC modes and the positions of bifurcation transitions between different modes. All previous studies explore either one or the other dimension but not the two together. As far as the Brown and Galbraith (2016) paper is concerned, it does not aim to produce a stability diagram of AMOC. They

performed a set of quasi-equilibrium simulations of the climate for different combinations of CO₂, ice sheets and orbital parameters, as well as several transient water hosing experiments.

- Significant mode shifts and overshoots on the hysteresis cycles are not discussed in the text. In particular, in Figure 1, the transition in the red solid line around 0.05Sv is remarkable: Is it different from an overshoot? Why is it sustained for about 1000 years? Could this be an occurrence of millennial-scale variability? Could you link this to Willeit 2024?

We will add the following text to clarify this:

This abrupt AMOC weakening is linked to the DO-variability produced by the model in the presence of noise, as shown in Willeit et al. (2024), and the associated overshoot in Fig. 1 is actually attributable to a missed initiation of millennial-scale oscillations.

- The definition of the different states comes too late in the paper and lacks precision. How do you define the different modes, using the AMOC index, the mixed layer depth or manually? Additionally, How do you calculate the AMOC index? What references did you use for the modern-day deep water formation sites, and how do they compare to your modern mode? Over what time slices was Figure 3 plotted?

The different modes are defined based on the mixed layer depth in different regions in the North Atlantic, as detailed below. This will be explicitly added to the caption of Fig. 4. The modern-day is characterized by deep water formation in the Labrador Sea and the Nordic Seas, which matches the locations with a deep mixed layer in the Modern AMOC state. Similarly to Fig. 6, also the AMOC states in Fig. 3 are for the boundary conditions of 400 ppm and 0.05 Sv, where all 4 AMOC states co-exist in the model. This will be added to the caption for clarification.

- The interpretation of the freshwater flux needs to be clarified in this article, and it becomes a problem when comparing pre-industrial to modern conditions. Would it not be more accurate to account for changes in CO₂ and freshwater forcing when comparing the two? Otherwise, what is the point of using a two-dimensional landscape? In addition, the following statement from the conclusion “Our results indicate a generally stronger and deeper AMOC at equilibrium under warmer climate conditions. This is in contrast to the projected AMOC weakening response to anthropogenic global warming [...]” is only valid if one considers the sole CO₂ effect, but freshwater forcing is expected to increase with Greenland melt, which could take us into a region of the landscape where all four modes exist. I think the comparison between past, present and future states should include a discussion about the role of excess freshwater induced by ice sheet melting.

Our stability diagram shows the equilibrium states of the climate (atmosphere-ocean-sea ice-land) system with fixed present-day ice sheets. Past or future freshwater flux from the surrounding ice sheets is considered as the external forcing and thus is the second dimension. We will add the following text to the ‘AMOC hysteresis in freshwater space’ section to clarify this point:

The FWF, as used in this study, represents perturbations to the freshwater balance of the North Atlantic by factors external to the climate (atmosphere-ocean-sea ice-land) system, namely from changing land ice volume that is not accounted for in our simulations because we use prescribed present-day ice sheets.

Given the strongly transient nature of ongoing global warming it does not make sense to compare pre-industrial with present-day conditions in the context of the AMOC stability landscape. As already mentioned in the paper, the transient and equilibrium AMOC response to CO₂ are fundamentally different, with an increase in AMOC strength with increasing CO₂ under equilibrium conditions, but a weakening if the CO₂ increase is fast. The non-trivial relation between future projected AMOC evolution and the stability landscape will be investigated in a forthcoming paper. Also, to avoid possible confusion on the interpretation of the red dot in Fig. 4, we will remove it. It was originally simply intended to show the present-day CO₂ concentrations, but it could be misinterpreted in terms of the present-day AMOC state.

During glacial terminations, the anomalous freshwater flux into the North Atlantic exceeded 0.1 Sv and had a profound impact on the AMOC, while for present-day conditions and even for the whole considered range of CO₂ (up to 2xCO₂), the net freshwater flux from Greenland is small ($\ll 0.1$ Sv (Otosaka et al., 2023; Briner et al., 2020; Calov et al., 2018)) and has little effect on the AMOC. We will add this information to the revised manuscript. For higher CO₂, the future freshwater flux from Greenland can be significant, but for high CO₂, Greenland will melt completely in around thousand years, which is much shorter than the time needed to trace the stability diagram. This highlights again that the only sensible way to deal with net freshwater from ice sheets when tracing the AMOC stability diagram is to treat it as external forcing.

Similarly to what done in the abstract, also in the conclusions we will make clear that the statement ‘*Our results indicate a generally stronger and deeper AMOC at equilibrium under warmer climate conditions...*’ is strictly valid only if meltwater input from Greenland is small enough, which is clearly the case according to different studies cited above.

- The details about the construction of the stability landscape is lacking precision and its validity cannot be evaluated. This all the more important as you highlighted the dependence of the direction of variation in Figure 1,2 and B1.

We will add detailed information on how the stability landscape is constructed in the caption of Fig. A1:

Simulation pathways used to explore the stability of the four different AMOC states in the combined CO₂ and freshwater space plotted on top of the AMOC stability landscape shown in Fig. 4. The stability of the Off AMOC state in (a) was explored with simulations starting from a large FWF of +0.5 Sv and then gradually decreasing the FWF until the AMOC recovers, for all levels of CO₂. The stability of the Strong AMOC state in (d) was tracked in simulations starting from a large negative FWF of -0.5 Sv and then gradually increasing the FWF. For the investigation of the stability of the (b) Weak and (c) Modern AMOC states, the starting point were pre-industrial conditions, marked by the black dot. The black arrows indicate the primary path through the CO₂ and FWF space, from which subsequent experiments with varying FWF in different directions are initialized (green arrows). Since the Strong AMOC state is not stable for CO₂ lower than 280 ppm for the FWF range shown in the figure, the stability of the Modern AMOC state in (c) for CO₂ lower than pre-industrial is diagnosed from simulations initialized with a large negative FWF of -0.5 Sv, similarly to what done in (d) for the Strong AMOC state. The rate of change of the forcing in all the experiments is 0.02 Sv/kyr for FWF and 2 %/kyr for CO₂.

Specific comments

Abstract

- L8 - Can you briefly define the OFF and Modern AMOC states?

We will add the following brief description:

'Apart from an Off AMOC state with no North Atlantic deep water formation and a Modern-like AMOC with deep water forming in the Labrador and Nordic Seas as observed at present, ...'

- L11-12 ("In general, the model shows an increase in equilibrium AMOC strength for higher CO₂ levels.") - This does not reflect the actual nature of the work, which goes way beyond this sole aspect. This statement is valid for the standard CO₂ experiment in Figure 2, but not consistent with Figure 4 (ex. in Figure 4a, an increase of CO₂ can trigger a weak mode). The abstract needs not to focus only on the CO₂ experiment but also on the stability landscape.

See response to first general comment above.

Introduction

- L28 ("There is no consensus as to whether the AMOC is in a monostable or a bistable regime under present climate conditions") - This needs a reference; I am aware of discussions on the potential weakening of the AMOC, less so about the current state of the AMOC.

We will add a reference to the review paper by Weijer et al. (2019) and to Liu et al. (2017), who suggested that the AMOC is bistable at present based on observational constraints.

Results

- L59 ("In particular, there is a range of FWF over which the AMOC has two stable states has two stable states") – Can you be precise about the range of FWF you are talking about? It also depends on your definition of stability, as I would argue that the dip around 0.05 Sv in Figure 1 is a sign of instability.

We will specify that we are talking about: *'roughly between 0.01 and 0.17-0.18 Sv'*. Yes, the dip around 0.05 Sv marks the transition between the Modern and Weak AMOC states, but doesn't change the fact that in terms of hysteresis curve the AMOC has two stable states for any given FWF in the above-mentioned range.

- L61 - Does "preindustrial conditions" mean 0 Sv in this case? Also, according to the methods, this experiment has pre-industrial CO₂ concentrations but a modern-day ice sheet. I would be more careful about using "pre-industrial" conditions, what about "initial state" instead?

We will specify that pre-industrial conditions refer to 280 ppm of CO₂. We consider pre-industrial and present-day ice sheets to be the same, which is a very reasonable assumption.

- L63 (“suggesting a prominent role of convective instability”) - Could you show that this is a convective instability, showing deep water formation sites activity, for example?

The potential energy released by convective mixing as a function of time in the simulations shown in Fig. 1 in the paper is shown in Fig. 1 below, separately for the Nordic Seas and the Labrador Sea. The figure clearly shows the abrupt decrease of convective activity associated with the AMOC transitions, providing a clear indication of convective instability occurring in the model.

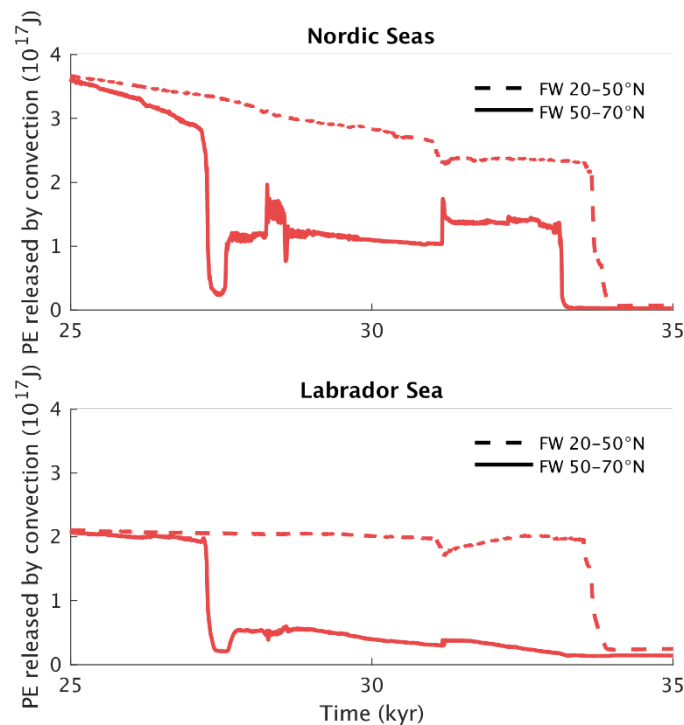


Figure 1 Potential energy released by convection in the Nordic Seas (above) and the Labrador Sea (below) as a function of time for the FWF hysteresis simulations with increasing FWF shown in Fig. 1 in the paper.

- L65 - “This is the result of a collapse of deepwater formation [...] of observed past Dansgaard-Oeschger events.” : Here again, the manuscript is missing a plot with the deep water sites dynamics to verify this statement, and a reference about convection in D-O records.

We are not aware of any direct reconstructions of convection locations during DO events. We will therefore remove the ‘observed’ in the sentence and add a reference to Willeit et al (2024), which includes a figure with the simulated mixed layer depth during DO Stadials and Interstadials.

- L67 – A definition of what the authors mean by Off, Weak, Modern-day, Strong is needed at this point of the paper.

We believe that at this point in the paper it is ok to simply refer qualitatively to the different AMOC states shown in Fig. 1, while a strict definition is given later, after all the different states have been gradually introduced.

- L82 (“which is possibly more relevant for the ongoing global warming”) - I disagree, both CO₂ and meltwater discharge are relevant to future climate changes.

We disagree and in the paper we have explained in detail why we think that the meltwater discharge from Greenland is small compared to the changes in the freshwater balance of the northern North Atlantic induced by changes in the hydrological cycle due to higher CO₂ (lines 133-137):

*For CO₂ doubling the net freshwater flux into the northern North Atlantic increases by ~0.07 Sv, an amount which is sufficient to cause a transition of the AMOC into a weak state if CO₂ is kept constant at pre-industrial values. 0.07 Sv is a relatively large freshwater flux, which is approximately **an order of magnitude higher than the net freshwater flux from the Greenland ice sheet simulated under similar temperatures** (e.g. Calov et al. (2018) and Briner et al. (2020)), and would roughly correspond to the rate of freshwater input resulting from the Greenland ice sheet melting completely over a time period of ~1500 years.*

- L85-93 - I find the wording of this section confusing. Is the rate of CO₂ increase in this paper slower than the “slow” increase in Gérard and Crucifix? How do you explain that you see a strengthening of the AMOC when Gérard and Crucifix 2024 saw a decrease? Could this simply mean that the AMOC response to CO₂ is highly uncertain and model dependent?

Considering also the comment by Gérard and Crucifix on our pre-print (<https://doi.org/10.5194/egusphere-2024-1482-CC1>), we have rewritten this paragraph: *Gérard and Crucifix (2024) recently analyzed the AMOC response to a slow CO₂ increase and found a gradual AMOC weakening and eventual collapse at CO₂ above ~1500 ppm. This is in contrast to our results, which show an increase in AMOC strength with increasing CO₂, at least up to a CO₂ concentration of 560 ppm. It should be noted that both in Gérard and Crucifix (2024) and in our study the CO₂ increase is slow enough to track the equilibrium AMOC response, but it has been shown that the AMOC response is highly sensitive to the applied rate of temperature change (Stocker and Schmittner, 1997).*

- L105 (“For CO₂ above ~250 ppm, the convection pattern resembles the present-day state with deep water forming in the Labrador Sea and in the Nordic Seas”) - Are you talking about Willeit et al. 2024 or this manuscript?

We are talking about this manuscript, which should be clear from the fact that later in the same sentence we are explicitly referring to Fig. 3c, which shows the mixed layer depth for the *modern* AMOC state.

- L156 (“If the climate would be in equilibrium with present-day CO₂ concentrations of ~420 ppm, the model suggests that the Modern AMOC state would not be stable, but that the AMOC would rather be in the Strong state instead”) – Back to the point about the interpretation of future freshwater forcing, would the accelerated melt of Greenland not move the system along the Modern AMOC conditions diagonal instead? Otherwise, this is a major caveat of the analysis that needs to be discussed

(although, arguably, the last paragraph of the discussion introduces this idea of model dependency).

Yes, the melt of Greenland would move the system in diagonal direction, but because freshwater input from Greenland melt is relatively small for the considered levels of global warming, the system would still be quite close to the FWF=0 axis. Also, as discussed above, this paper is really about the AMOC stability diagram and its relation to transient future climate and AMOC change will be the subject of further investigations.

- **Figure 4** - Good Figure but missing information about the criteria used for the clustering of the AMOC states. Is it purely based on the AMOC index, or on the mixed layer depth?

We will add the following text in the figure caption to clarify this:

The different states are formally defined based on a critical threshold ($mld_{max}^{crit}=600$ m) of the maximum mixed layer depth (mld_{max}) in three separate regions in the North Atlantic, namely (i) the Nordic Seas, (ii) the Labrador Sea and (iii) the Barents and Kara Seas and the Nansen basin.

Off: $mld_{max} < mld_{max}^{crit}$ in (i-iii);

Weak: $mld_{max} > mld_{max}^{crit}$ in (i) and $mld_{max} < mld_{max}^{crit}$ in (ii-iii);

Modern: $mld_{max} > mld_{max}^{crit}$ in (i-ii) and $mld_{max} < mld_{max}^{crit}$ in (iii);

Strong: $mld_{max} > mld_{max}^{crit}$ in (i-iii).

- **Figure 5** - I think this is the most important Figure of the paper and it deserves to be bigger. Also, why are the Off mode treated differently than the different modes? It makes the Figure difficult to interpret at first reading. Could you use different colours or shading and include all four states in the stability landscape?

We agree that this is the most important figure in the paper and will consequently make it larger. The Off state is in some sense fundamentally different from any of the 'on' states and it can not easily be framed in the general trend of AMOC becoming weaker with decreasing CO2 and increasing FWF, which is what the color shading is intended to represent.

Representing the Off state with the same color scheme would be problematic when e.g. considering the region of the landscape where the Strong and Off state are stable. What color would be associated to the coexistence of these two extreme states?

We will instead replace the crosses, which indicate the stability region of the Off state, with a white hatched area. White will therefore represent the Off state in the new figure, as shown in Fig. 2 below. This will hopefully make the figure easier to read and interpret. We will also add the following text to the figure caption:

The filled white area indicates where only the Off AMOC state is stable, while the white hatched area shows the domain where the Off AMOC state and one or more of the three 'on' AMOC states coexist.

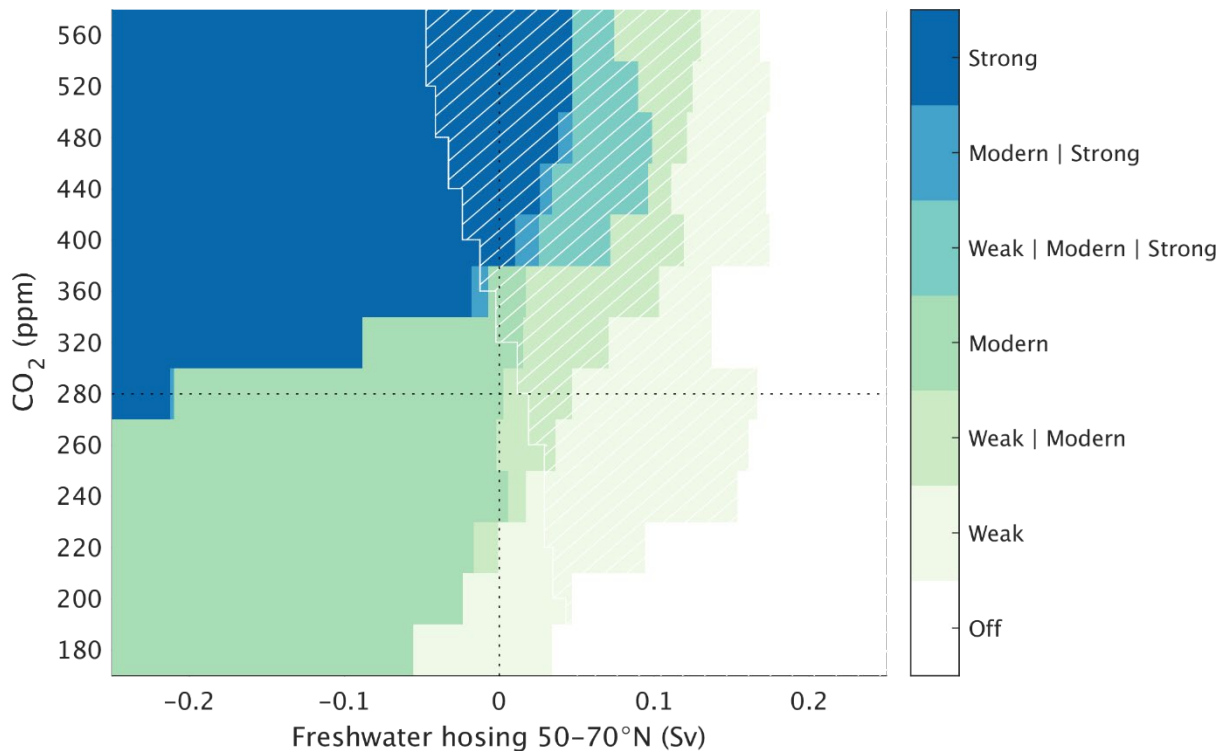


Figure 2 Revised Fig. 5.

- L181 - This is a good section and a convincing way to perform this analysis. However, as you showed, the sea ice extent is driving the most significant temperature changes, so I think it would be good to conclude on the impact of less extensive Arctic sea ice in future climate on these results.

We will add the following sentence to clarify this point:

While the temperature differences in Fig. 6 are representative of the impact of the different AMOC states on climate, they are strictly valid only for an atmospheric CO₂ of 400 ppm and a freshwater forcing of 0.05 Sv and could differ if the transition between AMOC states occurs under different boundary conditions.

Discussion

- L186 - Can you say a word about the Modern and Off AMOC modes.

We will add some more information on these two states as follows:

Apart from an Off AMOC state with no North Atlantic deep water formation and a Modern-like AMOC state with deep water forming in the Labrador and Nordic Seas as observed at present, ...

SI

- L256 - The paths used in **Figure A1** need to be clearly explained in the Figure or the text, otherwise it is impossible to validate the protocol in Figure 4. Do they

correspond to the black or the green arrows? Do they include the standard experiments?

We will explain in detail the paths in Fig. A1 in an expanded caption:

Simulation pathways used to explore the stability of the four different AMOC states in the combined CO₂ and freshwater space plotted on top of the AMOC stability landscape shown in Fig. 4. The stability of the Off AMOC state in (a) was explored with simulations starting from a large FWF of +0.5 Sv and then gradually decreasing the FWF until the AMOC recovers, for all levels of CO₂. The stability of the Strong AMOC state in (d) was tracked in simulations starting from a large negative FWF of -0.5 Sv and then gradually increasing the FWF. For the investigation of the stability of the (b) Weak and (c) Modern AMOC states, the starting point were pre-industrial conditions, marked by the black dot. The black arrows indicate the primary path through the CO₂ and FWF space, from which subsequent experiments with varying FWF in different directions are initialized (green arrows). Since the Strong AMOC state is not stable for CO₂ lower than 280 ppm for the FWF range shown in the figure, the stability of the Modern AMOC state in (c) for CO₂ lower than pre-industrial is diagnosed from simulations initialized with a large negative FWF of -0.5 Sv, similarly to what done in (d) for the Strong AMOC state. The rate of change of the forcing in all the experiments is 0.02 Sv/kyr for FWF and 2 %/kyr for CO₂.

- **Figure B2** does not have a caption.

We apologize for having overlooked the missing caption and will add the following caption to Fig. B2:

Change in the net freshwater flux into the ocean as a function of global temperature change in transient historical and future simulations under the SSP2-4.5 scenario until the year 2300 CE for (a) the northern North Atlantic and Arctic (north of 50° N) and (b) the whole Atlantic ocean. The solid line is for CLIMBER-X results and the circles represent CMIP6 model results.

Technical corrections

Introduction

- L17 - Do you have an example of a “societal” change?

We will remove ‘societal’ as we focus only on the climate impact.

- L19 - Add Bellomo 2021 for state-of-the-art climate model references.

We will add a references to Bellomo et al. (2021), Weijer et al. (2020), Weaver et al. (2012) and Romanou et al. (2023).

Results

- L51 – “Willeit et al. (2020)” to “(Willeit et al., 2020)

Will be fixed, thanks.

- L69 (“most AMOC hysteresis experiments to date have been performed with FWF at lower latitudes (usually between 20N and 50N)”) – Needs references.

We will add a reference to Rahmstorf et al. (2005), Hu et al. (2012) and van Westen and Dijkstra (2023).

- L71 (“In our hysteresis experiment”) – Change to “In Figure 1”, there are multiple hysteresis experiments in this paper.

We will change this to ‘In our freshwater hysteresis experiment in Fig. 1’.

- L80 (“give the wrong impression that the AMOC Off state is also stable”) – Is it a wrong impression or relative to the rate of meltwater discharge? Can you give an order of magnitude of the expected meltwater discharge for future melting or during a D-O event/Heinrich event?

The idea of the hysteresis experiments is to find the equilibrium states of the AMOC. To do this, the rate of change of freshwater forcing should be small enough to actually track the equilibrium states. The rate of change in our standard experiments is low enough to have confidence that the produced stability diagram is accurate enough. Obviously, the rate of change of 0.2 Sv/kyr corresponding to the dashed lines in Fig. B1 is not low enough and therefore the hysteresis curve produced with such rate of changes is wrong. These are idealized experiments that have little to do with past or future rates of meltwater discharge.

- L83 – “In an experiment where” to “In Figure 2”?

Will be changed as suggested.

- L94 (“two discrete transition”) - what do you mean by discrete? Abrupt?

We will replace discrete with abrupt.

- **Figure 2** - It is difficult to distinguish the solid and dotted lines on this Figure. Maybe two columns?

We will make the continuous lines in (a) slightly transparent, so that the dashed lines will be visible on top.

- L110 (“but this has been shown to not be a requirement for the existence of millennial-scale variability”) – Vague, can you say more?

We will expand the discussion of this point as follows:

A narrow window of CO₂ concentrations exists for which both convection patterns are stable for the same CO₂, but in Willeit et al. (2024) it was shown that this bistability is not a requirement for the existence of millennial-scale variability, for which it is sufficient that the system is close to where the abrupt AMOC transition between two different states occurs in the phase space of CO₂.

- **Figure 3** - The Figure needs to be bigger. Please add labels to the colour-bars. Does seasonal mean winter in this case?

We will either make the figure bigger, if possible for ESD standards, or alternatively switch rows and columns.

What is meant with ‘seasonal maximum’ is the monthly mean maximum over the year. We will change this to ‘maximum monthly mean...of the year’ the revised paper.

- L130 - “net freshwater flux” to “net surface freshwater flux”.

Will be changed.

- L133 (“for CO2 doubling”) – I would say “for double the amount of CO2” because you are not doing a CO2 doubling experiment, which, as you highlighted, could have a different impact on the AMOC.

Good point, thanks. Will be changed as suggested.

- L139 - “in the model the net surface freshwater flux into the whole Atlantic Ocean shows the opposite trend” to “the net surface freshwater flux into the whole Atlantic Ocean shows the opposite trend in our model”?

Will be changed.

- L144 - remove “a stabilizing effect”?

Will be removed.

- L150 - “can be investigating by tracing their stability through” to “can be investigated by tracing the AMOC response in”

Will be changed.

- L169 - “to explore the pure effect of the different AMOC states on climate” to “to isolate the effect of the changes of AMOC states on the climate”.

Will be changed.

- **Figure 6:** Can you use a different colour scheme for the temperature?

As suggested also by reviewer #3, we will change the color scale to make the figure easier to read.

Discussion

- L193 - “explains” to “demonstrates”?

Will be changed to avoid repetition in the use of ‘explains’.

- L202 (“anthropogenic global warming”) - Add Bellomo 2021 to the references for state-of-the-art climate models.

We will add a citation to Bellomo 2021.

SI

- **Figure B1:** Hard to distinguish the solid and dotted lines on this Figure. Maybe two columns?

We think that it is useful to see all three curves in the same figure to have a direct comparison between the three rates and the different curves seem to be well distinguishable where they don't overlap, which is what we are interested in.

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