Reviewer #3

Using a fast, low-resolution Earth system model, the authors present a systematic and comprehensive exploration of the dynamical stability landscape of the AMOC under quasi-equilibrium forcing conditions. Notably, AMOC stable states are explored in a combined phase space of atmospheric CO2 concentration and North Atlantic freshwater forcing. One of their main results is the possibility for a presence of more than two stable AMOC states if the present-day CO2 concentration and freshwater forcing are run into equilibrium. Among these, there is a stable “off” state, but also a stable “strong” state with deep water formation in the Kara Sea.

This study is a very timely and useful contribution to the discussion about the near-term evolution of the AMOC – a discussion that has very recently gained much traction again. Knowledge of AMOC stability in quasi-equilibrium climates – as opposed to the fast-changing transient that is our reality – is essential context for the scientific understanding of the latter.

The paper is very well written and has a clear layout. I offer a few comments for the authors to consider while recommending the ms. for publication without a further round of reviews.

We would like to thank the Reviewer for the positive appraisal of our work and the comments on our manuscript.

Comments

The study explores a range of CO_2 concentrations between 180 and 560 ppm. Of course this is a reasonable choice given the pre-industrial concentration. Sadly though, it is not entirely unlikely that the Earth System might have a CO_2 concentration larger that 560 ppm in the foreseeable future. Could the authors comment on why they didn’t explore that part of the phase space?

We restricted our study to concentrations below 560 ppm for two main reasons:
1) there is nothing fundamentally different happening in the model for CO2 concentrations between 560 and ~800 ppm that would warrant its inclusion in the paper,
2) for CO2 above ~800 ppm the model produces pronounced spontaneous oscillations in the formation of Antarctic bottom water, which then also affects the AMOC and substantially complicates the interpretation of the results. This feature could potentially be addressed in a separate study.

CLIMBER-X does not have internal interannual climate variability, as stated on l.220. The presence of such variability could lead to some states being indistinguishable (as said on l.222). Another possibility is that a stable state, while technically present, is occupied only with a very small probability (Monahan [2002], JPO 32, 2072-2085).

Indeed, the presence of internal variability ("noise") can destabilise some modes of the AMOC circulation that are stable in the absence of noise. The presence of noise can lead to spontaneous transitions between different AMOC modes, as demonstrated in another paper (Willeit et al., 2024 Climate of the Past Discussion) devoted to the Dansgaard-Oeschger events. The presence of a strong internal variability in GCMs can make the tracing of the AMOC stability diagram like shown in Fig. 4 problematic, if not impossible. In this sense,

the absence of such variability in CLIMBER-X is actually an advantage of the model, since it allows us to obtain the phase portrait of the system without noise and then to simulate realistic dynamical behaviour of the system by adding the noise.
We will add this information to the last paragraph of the paper:
Since CLIMBER-X does not produce internal interannual climate variability it is possible that different modes of the AMOC, which are distinct in our simulations, may not be distinguished in the presence of strong variability (e.g. Monahan, 2002). The presence of noise can also lead to spontaneous transitions between different AMOC modes, as demonstrated in Willeit et al. (2024). Intrinsic internal variability in general circulation models can make the tracing of the AMOC stability landscape problematic. In this sense, the absence of such variability in CLIMBER-X is actually an advantage of the model, since it allows to obtain the phase portrait of the system without noise and then to simulate realistic dynamical behaviour of the system by adding the noise.

For the three quantities plotted in Figure 2 we need the spatial context. Where, in e.g. latitude and depth, did you diagnose the AMOC maximum and the AMOC heat transport maximum? Is the delta net FW in panel (c) diagnosed over the entire surface of the Atlantic basin?

The AMOC strength is defined as the maximum of the AMOC streamfunction deeper than 700 m. This will be explicitly added to the caption in Fig. 1 and 2. The 'AMOC heat transport' label in panel 2b should read 'Atlantic heat transport' and is further explained in the caption: 'maximum meridional heat transport by the ocean in the Atlantic' should be clear enough, as the meridional heat transport is a function only of latitude and the maximum therefore unambiguously refers to the latitude where the heat transport is largest.
Panel (c) shows the delta net FW separately for the whole Atlantic and the North Atlantic north of 50°N as stated in the legend. To make it clearer we will also add this information to the caption.

I have one concern that I'd like the authors to comment on. Figure 3g tells us that the overturning streamfunction of the "modern" AMOC state shows a complete absence of the abyssal AABW (Antarctic bottom water) cell. We know that in reality the AABW cell is present (Talley et al. [2003], J. Clim. 16, 3213-3226; Johnson [2008], DOI 10.1029/2007JC004477). Does that imply that the CLIMBER-X phase space significantly deviates from present-day conditions? Or should we say that the state labelled "weak" here is the actual modern-day state? Fig. 3f, after all, displays the correct shape of the streamfunction, and Fig. 2a suggests that the amount of overturning is realistic in this "weak" state too. If the model did have variability, perhaps it would convect in the correct regions too?

First, we would like to note that the term "Modern" does not mean "present-day". The AMOC states and mixed layer depth fields shown in Fig. 3 are all for the same boundary conditions of 400 ppm of CO_2 and FWF of +0.05 Sv, i.e. for the boundary conditions under which all four AMOC states exist in the model. The states shown in Fig. 3 are therefore fully consistent with the plots in Fig. 6. This was not clear in the original paper, but will be made explicit in the caption of the figure in the revised manuscript. For the present-day, the simulated vertical profile of the AMOC streamfunction at 26°N compares reasonably well with the observations from the RAPID array (Fig. 1 below). However, it is true that the simulated AMOC in the model reaches a bit too deep and fills the whole Atlantic. It is also noteworthy that most CMIP6 models show the opposite bias, with a too shallow simulated AMOC (see Fig. 1 below). At present, CLIMBER-X also simulates an AABW cell of a

reasonable strength (e.g. Fig. 11 in Willeit et al. (2022)).
In terms of the mixed layer depth it is clear that the Modern AMOC state resembles much more closely the observed present-day pattern with deep water forming in the Labrador and Nordic Seas (Fig. 3b,c) and at least the application of noise in the form of random perturbations in the surface freshwater flux in the northern North Atlantic does not affect the locations of deep water formation in the model.
We will add the Fig. 1 below to the methods section of the revised paper, together with the following text:
In particular, the simulated present-day AMOC overturning profile at 26°N in the Atlantic is close to observations (Fig. A1), although it reaches a bit too deep. The present-day deep convection patterns compare well to ocean reanalysis in the North Atlantic (Fig. 13 in Willeit et al. (2022)).

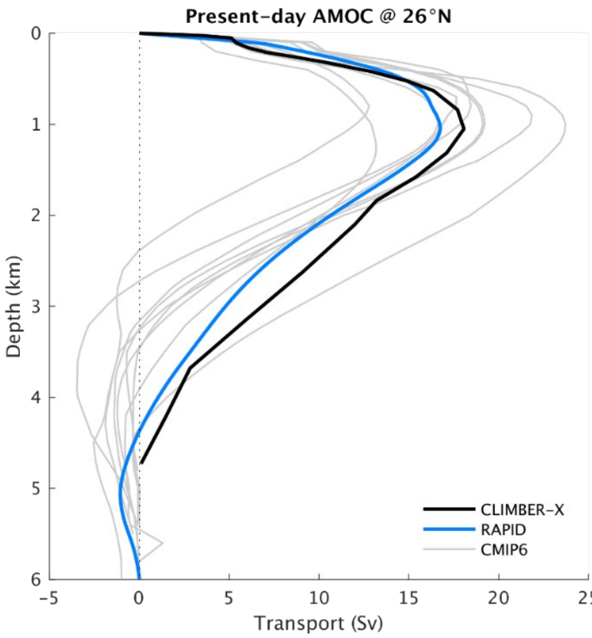

Figure 1 Profiles of the AMOC streamfunction at 26°N for the present-day. CLIMBER-X (black) is compared to observations from the RAPID array (blue) and a number of CMIP6 models (grey).

Could you consider a different type of colour scale for Figure 6? Currently it's really hard to work out the displayed colling patterns quantitatively using the small hue difference from one colour level to the next.

As suggested also by reviewer #1, we will change the color scale to try to make the figure easier to read.

When discussing Figure 6 (around lines 170 to 180), could it be worthwhile mentioning that an AMOC transition as in Figure 2a, driven by increasing CO2 concentration, would trigger a Modern to Strong transition, and thus a warming actually, with the negative of the patterns in Figure 6 b, f, j?

Absolutely, we will add the following text to the revised paper:
A slow increase in the CO2 concentration would trigger a Modern to Strong AMOC

transition as shown in Fig. 2a, and thus a warming actually, with the negative of the patterns in Fig. 6b,f,j.

I think for Figure B2 no legend was provided.

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.