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Version: Revision

Title: A Saddle-Node Bifurcation is Causing the AMOC Collapse in the Community Earth System Model

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Point-by-point reply to reviewer

August 31, 2025

We thank the reviewer for their careful reading and for the useful comments on the manuscript.

General Comments: This paper investigates the mechanisms behind Atlantic Meridional Overturning Circulation (AMOC) collapse in the Community Earth System Model (CESM). The paper aims to demonstrate that the classical picture of a saddle-node bifurcation, as exhibited by box models, also holds for the AMOC collapse in the CESM. This is done by analyzing pre-industrial CESM simulations and comparing them with a conceptual model (E-CCM). The authors use physical arguments to demonstrate that the complex behavior of AMOC in the CESM can be approximated by a reduced-order model, in which a saddle-node bifurcation drives the AMOC collapse.

These results underscore the utility of idealized AMOC models and may help evaluate the effect of model biases on the AMOC stability landscape and for understanding AMOC responses under various climate change projections. The careful experimental design and related analyses, for simulations in CESM and E-CCM, are commendable. I think the paper may be suitable for publication after the following issues are satisfactorily addressed.

Specific Comments

1. *The paper needs a discussion of the normal form of a saddle-node bifurcation and its properties (this could be in the appendix), given that the central aim of the work is to establish that the AMOC, as represented in CESM, has a saddle-node bifurcation. The strongest evidence for this*

is the square root dependence of the AMOC strength on the freshwater hosing in the reduced-order model developed from physical arguments. However, the paper does not explain why one should expect to see this square-root dependence.

Author's reply:

We agree that a better introduction of the saddle-node bifurcation and the associated square-root dependence is needed in the manuscript. We will include a new appendix (now appendix A) in the paper and refer to that in the introduction.

Changes in manuscript:

We will revise the text accordingly.

2. *Lines 391-394: Is the second argument in support of the existence of a saddle-node bifurcation in CESM qualitative? Does the 'two-times' faster transition in the 'half-rate' hosing experiment have any quantitative significance? Isn't this related to the inertia associated with the system? Lines 150-151 claim that this is a typical characteristic of transitions near saddle-node bifurcations. Could you explain this in more detail? I was unable to verify this claim by going through Kuehn 2011. In summary, I think the authors need to precisely clarify how this observation constitutes evidence for the existence of a saddle-node bifurcation.*

   Author's reply:

   The two times faster transition in forcing space for the half rate experiment is a characteristic of a saddle-node bifurcation (Berglund & Gentz (2006, https://link.springer.com/content/pdf/10.1007/1-84628-186-5_3.pdf, Li et al. Physica D, 395, 7-14, (2019)), but we agree that this should be further clarified.

   Changes in manuscript:

   We will clarify this characteristic in the new appendix A and refer to it when presenting the results of this CESM experiment.

3. *The addition of tables would be helpful for readers to keep track of the many simulations (CESM, E-CCM, and reduced-order model) used in*

this work. Please include details such as type (QE, branched from QE, steady state), duration, forcing characteristics, etc.

Author's reply:

Agreed, a table of the CESM simulations is useful for the reader. For the E-CCM (with the many sensitivity experiments) such a table would be too extensive.

Changes in manuscript:

We will include an overview of the presented CESM simulations in the revised Methods section.

4. *For completeness, I would suggest including a brief discussion of the 5-box model (Section 2.2), such as a short description of the different boxes.*

Author's reply:

Suggestion followed.

Changes in manuscript:

We will expand the description of the E-CCM in the revision.

5. *Line 125: In theory, would it have been better to run the half-rate forcing experiment, branching off from a much lower value of freshwater forcing? Is a shorter overshoot (in F_H) the only difference you would expect to see, compared to existing results?*

Author's reply:

It would indeed be better to run the half-rate forcing experiment, starting further from the saddle-node bifurcation, but this is computationally too expensive. However, we expect similar results as the standard quasi-equilibrium remains closer to the statistical equilibria for lower $\overline{F_H}$. The differences become larger when moving closer to the saddle-node bifurcation.

Changes in manuscript:

We will further elaborate on the half-forcing rate simulation in the revision.

Technical Comments

1. *Figures 2 and 5: The font size of the text in the subfigures is too small.*

   Author's reply:

   Panels c through n can share their y-axis to display them at a larger size.

   Changes in manuscript:

   We will revise Figures 2 and 5.

2. *Figure 5 (a,b): What causes the large overshoot in the backward quasi-equilibrium simulations after tipping back to the AMOC-on state?*

   Author's reply:

   The large overshoot is a model artefact and is not related to the dynamics of the E-CCM. This has been discussed in greater detail in van Westen et al. (2024b, https://doi.org/10.1175/JCLI-D-24-0060.1).

   Changes in manuscript:

   We will briefly mention this in the revision.

3. *Line 10: Typo: Should it be 'scenarios' (without the apostrophe)?*

   Author's reply:

   Agreed.

   Changes in manuscript:

   Will be corrected.

4. *Line 37: 'whether also this behavior' reads a bit awkward.*

   Author's reply:

   Agreed.

   Changes in manuscript:

   We will rewrite this as: '.... whether this behavior is also caused ...'

5. *Lines 166-167: Missing a 'to' in 'lower compared the'*

   Author's reply:

   Agreed.

   Changes in manuscript:

   Will be corrected.

6. *Line 387: Should it be 'built'?*

   Author's reply:

   Agreed.

   Changes in manuscript:

   Will be corrected.

7. *Line 391: What do you mean by 'with parameters somehow tuned'?*

   Author's reply:

   The E-CCM with sea-ice insulation effects was tuned to the CESM. These sea-ice effects were not considered in this manuscript, we only use the E-CCM in the temperature-varying and salinity-varying configuration.

   Changes in manuscript:

   We will remove this in the revision.