

Arctic climate tipping points under delayed CO₂ emissions mitigation

Corresponding Author: Mr You-Ting Wu

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The manuscript presents analysis of a modeling experiment with different CO₂ emission scenarios where emissions are then set to zero. The authors analyze Arctic amplification responses to the different scenarios. The authors found Arctic surface air temperature and sea ice area exhibit nonlinear and bifurcating behavior characterized by either continued warming and sea-ice loss (for total emissions less than 1700 PgC), or abrupt cooling and sea-ice expansion (for total emission greater than 1700 PgC).

I found this to be an interesting study with some non-intuitive conclusions, i.e., the Arctic cools and sea ice expands faster for higher emission scenarios and higher global air temperatures than lower emission scenarios and cooler global temperatures.

My biggest concern is the ability of the GISS GCM to correctly simulate all the moving parts necessary to capture this bifurcating behavior or tipping point at 1700 PgC and whether the AMOC collapses or not. The authors presented a comparison of the GISS model with other GCMs participating in ZECMIP in the extended data, and despite what the authors claimed I did not find the GISS model similar in behavior to the other models and to my eye it seemed to diverge, especially in terms of the Arctic and the AMOC. I would like to see evidence that the GISS model simulates Arctic surface air temperature, sea ice area and the AMOC in the current climate correctly before recommending acceptance of the manuscript.

I have a more minor suggested edit below. I recommend that the manuscript be accepted pending major revisions.

Minor comment:

Line 119 – I am having a hard time seeing the bifurcation point at 650ppm in panels 3c and 3d.

Reviewer #2

(Remarks to the Author)

This manuscript presents a compelling and timely investigation of Arctic climate responses under zero-emissions scenarios, with a particular focus on nonlinear behaviour and potential tipping points. By extending the ZECMIP framework to a wider range of cumulative emissions and employing an emissions-driven Earth system model, the study provides valuable insights into post-mitigation climate dynamics.

The identification of a bifurcation in Arctic temperature and sea-ice responses, linked to changes in the Atlantic Meridional Overturning Circulation (AMOC), is particularly interesting and potentially impactful. The manuscript is generally well structured, and the figures effectively support the main conclusions. I find the study to be relevant and promising, and I offer the following comments to further strengthen the clarity and robustness of the work.

Major Comments

1. The manuscript interprets the bifurcation in Arctic responses as evidence of a tipping point. While the results are suggestive and physically plausible, it would be helpful to further clarify how this behaviour aligns with standard definitions of tipping elements. In particular: To what extent is the transition robust across ensemble members? Is the behaviour better characterised as deterministic or stochastic? Are there indications of threshold-like or hysteresis behaviour? A short

clarification would strengthen the interpretation and avoid potential overstatement.

2. The results are primarily based on a single model configuration (GISS ModelE2.1-G-CC2), with limited comparison to ZECMIP simulations. Given the central role of AMOC behaviour in driving the Arctic response, further discussion of model dependence would be valuable. How representative is the simulated AMOC sensitivity relative to other CMIP6 or ZECMIP models? To what extent might the identified threshold depend on model-specific processes?

3. The energy budget analysis (Fig. 4) is a strong component of the manuscript and already provides a quantitative comparison of different contributions. To further enhance clarity, it would be helpful to more explicitly summarise the relative importance of ocean heat transport changes versus radiative feedback. In particular, a clearer statement of the hierarchy among these processes (e.g., which terms act as the primary driver versus amplification, and their relative magnitudes) would make the physical interpretation more immediately accessible to the reader.

4. The transition is identified between 1500 and 1700 PgC, but the precise threshold remains somewhat uncertain. It would be useful to briefly discuss: Whether additional intermediate simulations could help constrain this range; Or how sensitive this threshold might be to model configuration or experimental design. Such clarification would help frame the result in terms of uncertainty.

Minor Comments

L134: "surface-albedo" -> "surface-albedo"

Figure 2 g-i labels: "SAT" -> "SIA"

The identification of ~1700 PgC as a threshold is interesting. It would be valuable to indicate the corresponding global mean temperature at this point in the model, to facilitate comparison with policy-relevant thresholds (e.g., 1.5°C and 2°C targets).

Reviewer #3

(Remarks to the Author)

The manuscript shows that Arctic climate can exhibit divergent behavior under a carbon reduction scenario: one pathway involves continued warming and declining Arctic sea ice when the AMOC remains active, whereas the other involves cooling and sea-ice expansion when the AMOC collapses.

Overall, I found the paper very interesting and already in very good shape. I would also note that this study is closely related to the recently identified AMOC tipping behavior (<https://www.nature.com/articles/s41467-025-66494-1>). While that study highlighted the divergent AMOC response itself, the present study further demonstrates that its influence extends to the Arctic climate.

In my view, the manuscript is publishable after minor revision.

1. It would be helpful to include a figure that directly illustrates the relationship between Arctic temperature and AMOC strength (e.g., similar to Fig. 3). This would strengthen the interpretation of the proposed mechanism linking AMOC changes to Arctic climate response.

2. The AMOC behavior discussed in this manuscript appears to be essentially identical to that reported in a recent study (<https://www.nature.com/articles/s41467-025-66494-1>). The authors should cite and discuss this work.

3. Across all figures, axis labels are often missing or unclear. For example, in Fig. 1(a), the y-axis appears to represent CO₂ concentration, but this is not explicitly labeled. All figures should clearly indicate the physical variables shown on both axes.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I thank the authors for their efforts to revise the manuscript. I am satisfied with the revised manuscript and have no further comments or suggested edits. I recommend that the manuscript be accepted.

Reviewer #2

(Remarks to the Author)

I thank the authors for addressing most of my previous comments and I'm happy to recommend acceptance in its current form.

Reviewer #3

(Remarks to the Author)

I have no further comments.

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Response to Reviewers

”Arctic Climate Tipping Points under Delayed CO₂ Emissions Mitigation”

You-Ting Wu, Michael Previdi, Anastasia Romanou, Paul Lerner, and Lorenzo M. Polvani

Communications Earth & Environment

May 13, 2026

We thank the Editor and three Reviewers for their careful reading of our manuscript and their constructive feedback. Below we provide a point-by-point response to each comment. All changes to the manuscript are highlighted in the revised text.

Reviewer #1

The manuscript presents analysis of a modeling experiment with different CO₂ emission scenarios where emissions are then set to zero. The authors analyze Arctic amplification responses to the different scenarios. The authors found Arctic surface air temperature and sea ice area exhibit nonlinear and bifurcating behavior characterized by either continued warming and sea-ice loss (for total emissions less than 1700 PgC), or abrupt cooling and sea-ice expansion (for total emissions greater than 1700 PgC).

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My biggest concern is the ability of the GISS GCM to correctly simulate all the moving parts necessary to capture this bifurcating behavior or tipping point at 1700 PgC and whether the AMOC collapses or not. The authors presented a comparison of the GISS model with other GCMs participating in ZECMIP in the extended data, and despite what the authors claimed I did not find the GISS model similar in behavior to the other models and to my eye it seemed to diverge, especially in terms of the Arctic and the AMOC. I would like to see evidence that the GISS model simulates Arctic surface air temperature, sea ice area and the AMOC in the current climate correctly before recommending acceptance of the manuscript.

Response: We appreciate the reviewer’s concern. To address it, we compared the GISS-ModelE2.1 historical simulation against observational datasets for global surface air temperature (SAT), Arctic SAT and Arctic sea ice area (SIA) (1980–2014), shown in Fig. R1. The model well reproduces observed warming trends well in both global and Arctic SAT over historical period, consistent with prior CMIP6 evaluations of GISS-ModelE2.1 (*Kelley et al.*, 2020; *Miller et al.*, 2021). The Arctic SIA in the model trends are somewhat weaker than the observed trend since 1980, but well within the CMIP6 ensemble (*Notz and Community*, 2020).

As for AMOC, *Miller et al.* (2021) and *Weijer et al.* (2020) document the AMOC behavior in the GISS E2.1 model that is used here in. Specifically, *Weijer et al.* (2020) show comparisons with both observations and other models. Fig. R2 shows the GISS E2.1 is within the other models’ distributions with depth, although 30% stronger than observations at depths of 2 km depth at RAPID (26°N) and 40% stronger than observations along the SAMBA array (34°S). Figure 2 in the same paper (Fig. R3 here) shows that the GISS E2.1 AMOC shows large declines which are still comparable to other models. It is known that models that overestimate AMOC in historical simulations exhibit the fastest declines in future climate scenarios. Such declines are seen in several other models, e.g. *Dijkstra and van Westen* (2026): Figure 2a (Fig. R4 here). The GISS E2.1 AMOC behavior compares well with other models. It has an important element however, which is the bifurcation at higher emission/warming levels that has been documented & explained in *Romanou et al.* (2023).

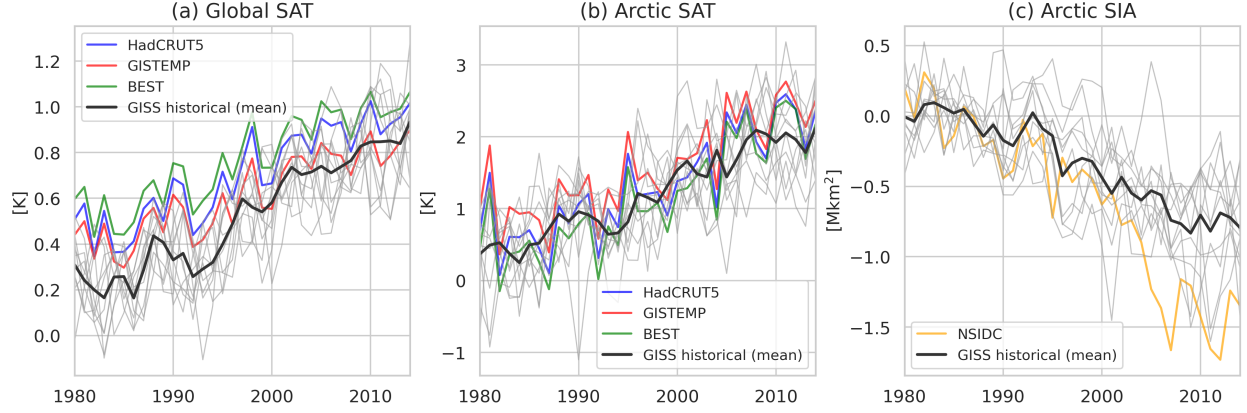


Figure R1. Historical validation of GISS-ModelE2.1 (black lines) against observations. (a) Global surface air temperature (SAT) anomaly relative to 1850–1859, compared with HadCRUT5, GISTEMP, and BEST. (b) Arctic (60° – 90°N) SAT anomaly. (c) Arctic SIA anomaly relative to 1980–1989, compared with NSIDC.

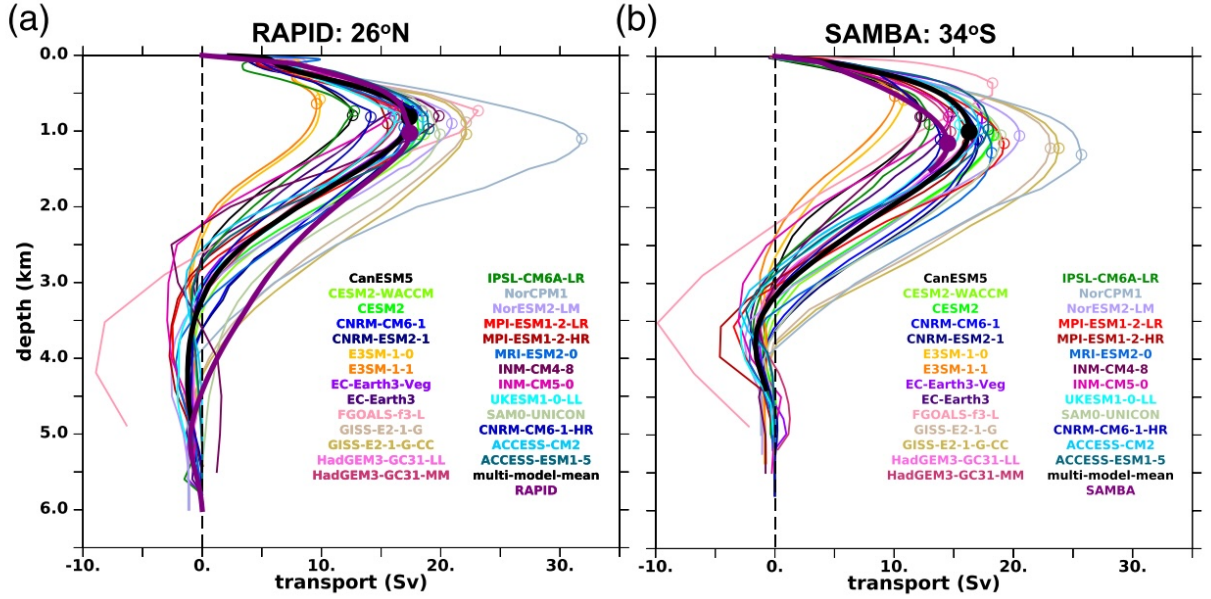


Figure R2. Annual mean overturning stream function as a function of depth at (a) 26°N and (b) 34°S , averaged over the RAPID observational period (April 2004 onward). One ensemble member per model is displayed given the typically small ensemble spread. Circles mark the depth of maximum stream function. Figure from *Weijer et al.* (2020).

Regarding the Extended Data comparison with ZECMIP: unfortunately, each ZECMIP model contributed only a single ensemble member, so we have no estimate of the internal variability in each model. However, our 6-member ensemble mean for global SAT lies within the mid-range of ZECMIP models across all scenarios.

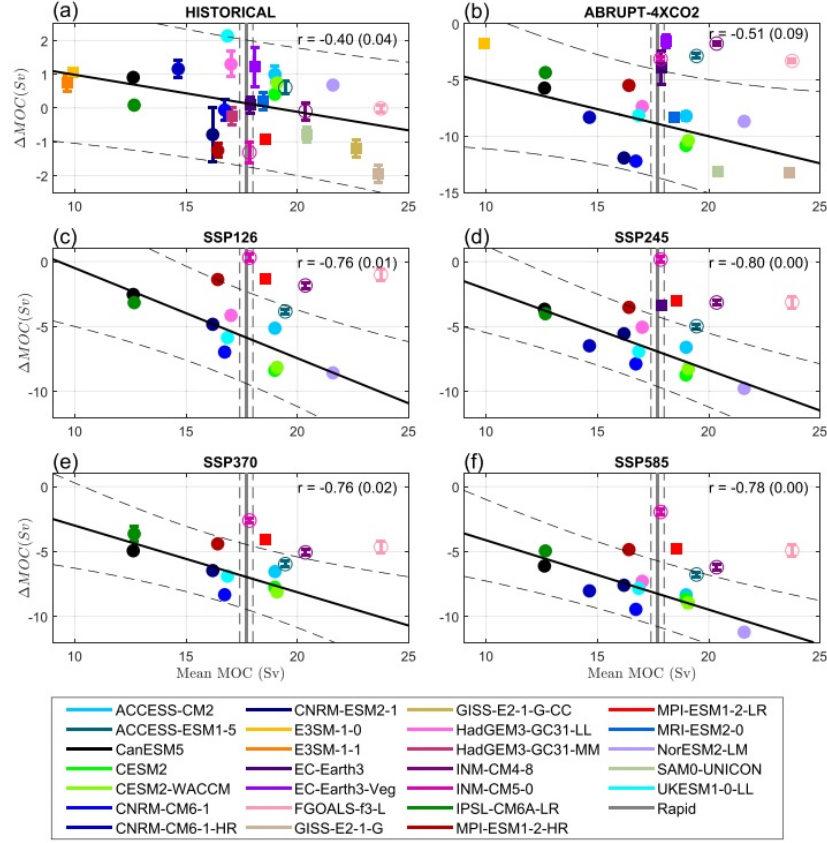


Figure R3. AMOC strength at 26°N averaged over the RAPID period versus AMOC change for (a) the historical simulation (RAPID period minus 1850–1859); (b) the abrupt $4\times\text{CO}_2$ experiment (decades 141–150 minus decades 1–10); and (c–f) the SSP scenarios (2091–2100 minus the RAPID period). Pearson correlation coefficients and p-values are given in brackets. Filled circles denote models in the majority cluster; open circles denote outlier models. Figure from *Weijer et al. (2020)*.

Minor Comment

Line 119: I am having a hard time seeing the bifurcation point at 650 ppm in panels 3c and 3d.

Response: We thank the reviewer for this comment. To guide the eye, we suggest focusing on the green (1500 PgC) and blue (1700 PgC) curves in Fig. 3c. Beginning at the filled circle labeled "S" (the start year of CO_2 cessation) and tracing each curve towards "E" (the end-year post-cessation), the two trajectories overlap while CO_2 is above ~ 650 ppm but diverge sharply once CO_2 drops below that level, as the green curve stabilizes while the blue curve continues to cool. The same bifurcation is visible in Fig. 3d for Arctic SIA, where the same two curves separate at the same CO_2 value but in the opposite direction.

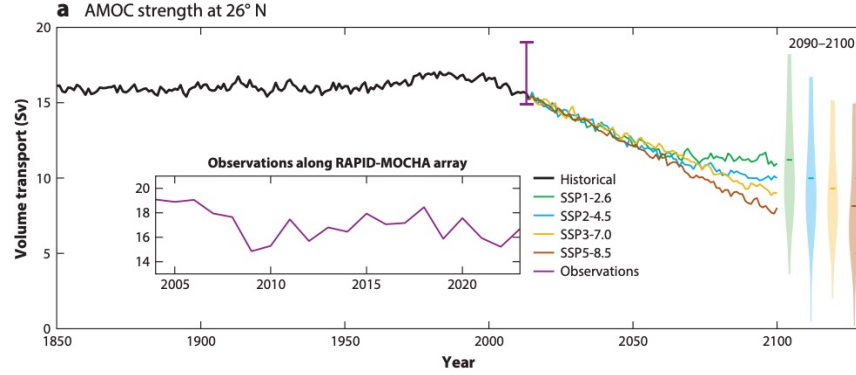


Figure R4. Maximum AMOC strength at 26°N during the historical period (1850–2014) and under SSP scenarios (2015–2100), based on the multi-model CMIP6 mean derived from 21 models. Violin plots illustrate the inter-model spread at the end of the twenty-first century, with horizontal bars indicating the multi-model mean. The inset displays the observed AMOC strength from the RAPID–MOCHA array, with the error bar denoting its minimum and maximum values. Figure from *Dijkstra and van Westen (2026)*.

References

- Dijkstra, H. A., and R. M. van Westen, The probability of an amoc collapse onset in the twenty-first century, *Annual Review of Marine Science*, 18, 2026.
- Kelley, M., et al., GISS-E2.1: Configurations and climatology, *Journal of Advances in Modeling Earth Systems*, 12(8), e2019MS002,025, 2020.
- Miller, R. L., et al., CMIP6 historical simulations (1850–2014) with GISS-E2.1, *Journal of Advances in Modeling Earth Systems*, 13(1), e2019MS002,034, 2021.
- Notz, D., and S. Community, Arctic sea ice in cmip6, *Geophysical Research Letters*, 47(10), e2019GL086,749, 2020.
- Romanou, A., et al., Stochastic bifurcation of the North Atlantic circulation under a midrange future climate scenario with the NASA-GISS ModelE, *Journal of Climate*, 36(18), 6141–6161, 2023.
- Weijer, W., W. Cheng, O. A. Garuba, A. Hu, and B. T. Nadiga, Cmp6 models predict significant 21st century decline of the atlantic meridional overturning circulation, *Geophysical Research Letters*, 47(12), e2019GL086,075, 2020.

Reviewer #2

This manuscript presents a compelling and timely investigation of Arctic climate responses under zero-emissions scenarios, with a particular focus on nonlinear behaviour and potential tipping points. By extending the ZECMIP framework to a wider range of cumulative emissions and employing an emissions-driven Earth system model, the study provides valuable insights into post-mitigation climate dynamics.

The identification of a bifurcation in Arctic temperature and sea-ice responses, linked to changes in the Atlantic Meridional Overturning Circulation (AMOC), is particularly interesting and potentially impactful. The manuscript is generally well structured, and the figures effectively support the main conclusions. I find the study to be relevant and promising, and I offer the following comments to further strengthen the clarity and robustness of the work.

Major Comment 1

The manuscript interprets the bifurcation in Arctic responses as evidence of a tipping point. While the results are suggestive and physically plausible, it would be helpful to further clarify how this behaviour aligns with standard definitions of tipping elements. In particular: To what extent is the transition robust across ensemble members? Is the behaviour better characterised as deterministic or stochastic? Are there indications of threshold-like or hysteresis behaviour? A short clarification would strengthen the interpretation and avoid potential overstatement.

Response: We thank the reviewer for this clarification request. Following *Lenton et al.* (2008), a tipping element is a subsystem of the Earth system that may switch into an entirely different state after a small perturbations in the forcing is applied to it and a critical threshold is crossed. Our results are consistent with this framework, though the transition is better characterized as stochastic rather than deterministic. Within a given scenario (e.g. 1500, 1700, 2000 PgC etc), six ensemble members are launched at the point of zero emissions in the 1%CO₂ run. Therefore, all ensemble members of each scenario share identical forcing conditions (CO₂ emissions) but differ in the phase of internal variability (e.g. ENSO phase, NAO phase etc). At the same point in time, some members will have stronger ENSO while some others will have weaker ENSO but generally the response to the forcing (linear trend) is expected to be the same. This is what typically done when modeling groups perform ensemble simulations to capture the chaotic (stochastic) variability of climate. Typically, under the same forcing, the stochastic variability in all ensemble members will average out over longer time periods, leaving only the response to forcing (the linear trend). However, when the internal variability becomes too large (compared to the forcing effect) we see "ensemble splitting" — the ensemble members might differ substantially. A similar behavior was documented in *Oh et al.* (2025). Here, in the case of scenarios 1500 & 1700 PgC, individual ensemble members diverge: some undergo AMOC collapse (Fig. 3a) and Arctic cooling (Fig. 1g), while others maintain a stable AMOC and continue warming. This spread demonstrates that internal variability, rather than forcing alone, determines which side of the threshold a given realization crosses (*Romanou et al.*, 2023). We added this discussion in Line 145–148.

Major Comment 2

The results are primarily based on a single model configuration (GISS ModelE2.1-G-CC2), with limited comparison to ZECMIP simulations. Given the central role of AMOC behaviour in driving the Arctic response, further discussion of model dependence would be valuable. How representative is the simulated AMOC sensitivity relative to other CMIP6 or ZECMIP models? To what extent might the identified threshold depend on model-specific processes?

Response: We thank the reviewer for this important question. Following Extended Data Figs. 1–3, our GISS simulations generally lie within the mid-range of ZECMIP models for global and Arctic surface air temperature across all scenarios, suggesting that while AMOC sensitivity differs across models, the overall climate response of our model is not an outlier. In addition, AMOC bifurcation under zero-emission scenarios is not unique to GISS. *Oh et al.* (2025) recently demonstrated a similar divergent AMOC behavior using CESM, an independently model with different ocean physics, giving further support to this mechanism. We have added this clarification to the Discussion (Line 156–159).

Major Comment 3

The energy budget analysis (Fig. 4) is a strong component of the manuscript and already provides a quantitative comparison of different contributions. To further enhance clarity, it would be helpful to more explicitly summarise the relative importance of ocean heat transport changes versus radiative feedback. In particular, a clearer statement of the hierarchy among these processes (e.g., which terms act as the primary driver versus amplification, and their relative magnitudes) would make the physical interpretation more immediately accessible to the reader.

Response: We thank the reviewer for this suggestion. Figure 4 shows a clear process hierarchy across all scenarios. In the lower-accumulation cases (800–1500 PgC), oceanic heat transport (OHT) anomalies range from approximately 1.5 to 2 Wm^{-2} while lapse-rate and surface-albedo feedbacks remain modest (0 to 1 Wm^{-2}). In the higher-accumulation cases (1700–2000 PgC), OHT anomalies reach approximately -3 Wm^{-2} , with lapse-rate and albedo feedbacks of -1.5 to -2 Wm^{-2} . Across both regimes, OHT emerges as the dominant term, with Arctic radiative feedbacks acting as secondary amplifiers that reinforce the OHT-driven response. We have added the above sentences to the manuscript (Line 134–138).

Major Comment 4

The transition is identified between 1500 and 1700 PgC, but the precise threshold remains somewhat uncertain. It would be useful to briefly discuss: whether additional intermediate simulations could help constrain this range; or how sensitive this threshold might be to model configuration or experimental design. Such clarification would help frame the result in terms of uncertainty.

Response: We thank the reviewer for this comment. We note that the 1500–1700 PgC range represents a stochastic tipping zone, within which internal variability determines whether a given realization crosses the threshold. Finer intermediate simulations (e.g. 1600 PgC) would help characterize the structure of this zone more precisely, and we propose this as future work (Line 160).

The precise location of this zone depends on several model factors, including: (1) the pre-industrial strength of the AMOC, which sets the baseline sensitivity to thermal perturbations; (2) the climate sensitivity of the model, which determines the global warming level reached at a given cumulative emission; and (3) a more complete understanding of the coupling between AMOC changes and energy budget. Improving these aspects across models would help narrow the threshold range. We added this discussion in Line 161–163.

Minor Comments

L134: "surface-albdeo" → "surface-albedo".

Response: Fixed. We thank the reviewer for catching this typo.

Figure 2 g-i labels: "SAT" → "SIA".

Response: Fixed. We thank the reviewer for catching this error.

The identification of ~ 1700 PgC as a threshold is interesting. It would be valuable to indicate the corresponding global mean temperature at this point in the model, to facilitate comparison with policy-relevant thresholds (e.g., 1.5°C and 2°C targets).

Response: We thank the reviewer for this suggestion. At the time of CO_2 emissions cessation, the global mean surface air temperature anomaly relative to preindustrial levels is approximately $+2.5$ K in the 1500 PgC scenario, where ensemble members begin to diverge, and $+2.7$ K in the 1700 PgC scenario. Both values already exceed the 2°C Paris Agreement target, suggesting that the Arctic tipping threshold would be breached under delayed mitigation consistent with global warming above 2°C . We added the discussion in Line 165–166.

References

- Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber, Tipping elements in the Earth's climate system, *Proceedings of the National Academy of Sciences*, 105(6), 1786–1793, doi:10.1073/pnas.0705414105, 2008.
- Oh, J.-H., J.-S. Kug, Y. Shin, et al., Noise-induced tipping of Atlantic Meridional Overturning Circulation under climate mitigation scenarios, *Nature Communications*, 16, 11,515, doi:10.1038/s41467-025-66494-1, 2025.

Romanou, A., et al., Stochastic bifurcation of the North Atlantic circulation under a midrange future climate scenario with the NASA-GISS ModelE, *Journal of Climate*, *36*(18), 6141–6161, 2023.

Reviewer #3

The manuscript shows that Arctic climate can exhibit divergent behavior under a carbon reduction scenario: one pathway involves continued warming and declining Arctic sea ice when the AMOC remains active, whereas the other involves cooling and sea-ice expansion when the AMOC collapses. Overall, the paper is found to be very interesting and already in very good shape.

Overall, I found the paper very interesting and already in very good shape. I would also note that this study is closely related to the recently identified AMOC tipping behavior (*Oh et al.*, 2025). While that study highlighted the divergent AMOC response itself, the present study further demonstrates that its influence extends to the Arctic climate.

In my view, the manuscript is publishable after minor revision.

Comment 1

It would be helpful to include a figure that directly illustrates the relationship between Arctic temperature and AMOC strength (e.g., similar to Fig. 3). This would strengthen the interpretation of the proposed mechanism linking AMOC changes to Arctic climate response.

Response: We thank the reviewer for this suggestion. We provide Fig. R5, which directly plots Arctic surface air temperature (SAT) against AMOC strength for all six scenarios. However, we think that our original Fig. 3b–d, which uses atmospheric CO₂ as the common axis, offers a clearer and more physical insight. Because CO₂ is the direct external forcing that evolves during post-cessation periods, it provides a cleaner frame across all scenarios. In contrast, when Arctic SAT is plotted against AMOC strength (Fig. R5), the trajectories become tangled and the direction of evolution is difficult to follow, making it harder for the reader to identify the bifurcation. We therefore prefer to keep Fig. 3 in its current form, as it more effectively communicates the link between AMOC changes and Arctic climate response via CO₂ axis.

Comment 2

*The AMOC behavior discussed in this manuscript appears to be essentially identical to that reported in a recent study (*Oh et al.*, 2025). The authors should cite and discuss this work.*

Response: We thank the reviewer for pointing this out. We have cited *Oh et al.* (2025) and added the discussion in the main text (Line 156–159).

Comment 3

Across all figures, axis labels are often missing or unclear. For example, in Fig. 1(a), the y-axis appears to represent CO₂ concentration, but this is not explicitly labeled. All

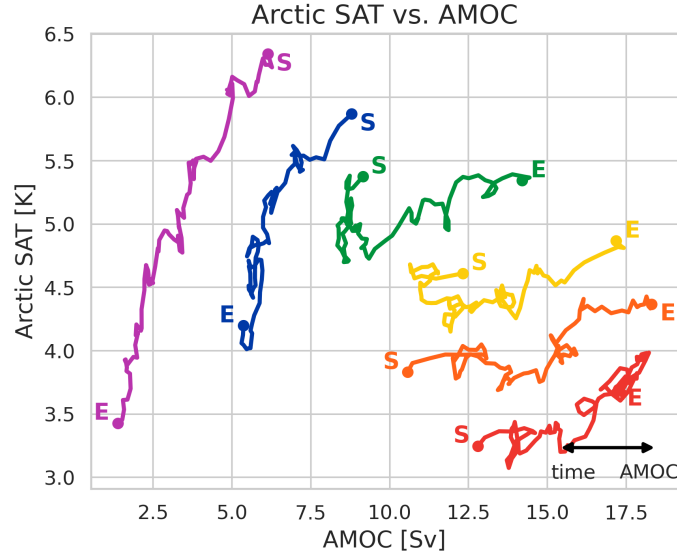


Figure R5. Same as Figure 3b but for Arctic SAT as a function of AMOC strength.

figures should clearly indicate the physical variables shown on both axes.

Response: We thank the reviewer for this careful detail. We have revised all figures to ensure both axes are explicitly labeled with the physical variable and units.

References

Oh, J.-H., J.-S. Kug, Y. Shin, et al., Noise-induced tipping of Atlantic Meridional Overturning Circulation under climate mitigation scenarios, *Nature Communications*, 16, 11,515, doi:10.1038/s41467-025-66494-1, 2025.