EDUSCHOOL
ACADEMIC RESEARCH & PUBLISHERS

EDUSCHOOL JOURNAL OF ENVIRONMENTAL
RESEARCH STUDIES (EJERS)

(Open Access, Double-Blind Peer Reviewed Journal)

ISSN Online:

Atlantic Overturning Circulation and Climate Tipping Points

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Article information

Received: 5th March 2026
Received in revised form: 8th April 2026
Accepted: 12th May 2026
Available online: 15th June 2026

Volume: 1
Issue: 1
DOI: https://doi.org/10.5281/zenodo.20696369

Abstract

The Atlantic Meridional Overturning Circulation (AMOC) transports approximately 1.3 PW of heat northward, sustaining the relative warmth of western Europe and influencing precipitation patterns across the tropics and subtropics. Multiple observational and proxy lines of evidence suggest that the AMOC has weakened over recent decades, raising concerns about a potential approach to a critical tipping point beyond which collapse could become irreversible. This study analyzes AMOC projections from eight CMIP6 Earth system models under the SSP5-8.5 scenario, finding a multi-model mean decline of 38 percent by 2100, from 17.7 Sv to 10.9 Sv. Bifurcation analysis applied to three models with freshwater hosing experiments reveals estimated collapse thresholds at 0.28 to 0.32 Sv of anomalous freshwater forcing, with hysteresis widths of 0.12 to 0.18 Sv indicating that recovery from a collapsed state would require substantially greater cooling than the warming that triggered the transition. Two of three analyzed models indicate a high risk of crossing the tipping point by 2100 under unmitigated emissions, with cascading consequences including northern European cooling, southward shift of the Intertropical Convergence Zone, disruption of West African and South Asian monsoons, and accelerated sea-level rise along the North American east coast.

Keywords:- AMOC, Tipping Points, Climate Change, CMIP6, Thermohaline Circulation, Bifurcation

I. INTRODUCTION

The Atlantic Meridional Overturning Circulation is the system of ocean currents that carries warm, saline surface waters northward through the Atlantic basin, where they release heat to the atmosphere, increase in density through cooling and evaporation, and sink to depth in the Nordic Seas and Labrador Sea to form North Atlantic Deep Water11. This deep water flows southward along the western boundary of the Atlantic at depths of 1,500 to 4,000 meters, completing the overturning cell. The AMOC transports approximately 1.3 petawatts of heat across the equator roughly 25 percent of the total poleward heat transport by the combined ocean-atmosphere system making it a fundamental regulator of Northern Hemisphere climate (Rahmstorf, 2002; Buckley & Marshall, 2016).

Paleoclimate evidence from ice cores, ocean sediment records, and speleothems documents multiple episodes of abrupt AMOC weakening or collapse during the last glacial period, notably the Younger Dryas cold reversal (12,900–11,700 years before present) and Heinrich events, during which massive iceberg discharges introduced freshwater pulses that disrupted deep-water formation (Rahmstorf, 2002). These past reorganizations were accompanied by rapid climate shifts temperature changes of 5 to 10°Cover Greenland within decades and global-scale teleconnections including southward displacement of the Intertropical Convergence Zone and disruption of Asian monsoon systems (Rahmstorf, 2002; Jackson et al., 2015).

Contemporary observations have raised alarms that the AMOC may be weakening under anthropogenic forcing. Caesar and colleagues reconstructed AMOC strength using a proxy index based on North Atlantic sea-surface temperature anomalies and found a decline of approximately 15 percent since the mid-twentieth century Caesar et al., 2018). Direct measurements from the RAPID-MOCHA monitoring array at 26.5°N, operational since 2004, recorded a statistically significant decline in AMOC transport of 2.7 Sv between 2004 and 2017, though the short observational record makes it difficult to distinguish trends from decadal variability (Smeed et al., 2018). Boers applied statistical early-warning indicators to multiple AMOC proxy datasets and detected a progressive loss of dynamical stability consistent with an approach toward a tipping point (Boers, 2021). Ditlevsen and Ditlevsen used advanced statistical methods to estimate that AMOC collapse could occur as early as the mid-2030s, though this projection carries substantial uncertainty (Ditlevsen & Ditlevsen, 2023).

This paper evaluates the risk of AMOC tipping under continued high emissions by analyzing projections from eight CMIP6 models and applying bifurcation theory to assess proximity to critical thresholds. We further examine the cascading impacts of AMOC weakening on European climate, tropical precipitation, and coastal sea levels to inform assessment of the consequences should this tipping point be crossed.

II. LITERATURE REVIEW

2.1. AMOC Observational Evidence

The RAPID-MOCHA monitoring array, deployed across the Atlantic at 26.5°N since April 2004, provides the longest continuous record of full-depth AMOC transport. Smeed and colleagues reported that mean AMOC strength during 2008–2012 was approximately 2.7 Sv weaker than during the initial deployment period of 2004–2008, though subsequent years showed partial recovery followed by renewed decline (Smeed et al., 2018). The mean AMOC transport over the full record period is approximately 17 Sv, with substantial seasonal and interannual variability (standard deviation of approximately 4 Sv) that complicates trend detection from direct observations alone.

Indirect evidence for longer-term AMOC weakening comes from proxy reconstructions. Caesar and colleagues developed a fingerprint index based on the observation that AMOC weakening produces a characteristic pattern of sea-surface temperature anomalies: cooling in the subpolar North Atlantic (the so-called 'warming hole') concurrent with warming in the Gulf Stream region (Caesar et al., 2018). Applying this index to instrumental temperature records, they estimated that the AMOC has declined by approximately 3 Sv (roughly 15 percent) since the mid-twentieth century, making it the weakest in at least a millennium based on comparison with paleoclimate proxy compilations. Buckley and Marshall reviewed the full suite of observational constraints on AMOC variability and concluded that while internal variability remains large, the evidence for anthropogenically forced weakening is strengthening (Buckley & Marshall, 2016).

2.2. CMIP6 Projections

Weijer and colleagues conducted a comprehensive review and synthesis of AMOC projections across CMIP5 and CMIP6 model ensembles, finding a robust decline under all warming scenarios but with substantial inter-model spread in both the rate and magnitude of weakening (Weijer et al., 2019). Under the CMIP6 SSP5-8.5 scenario, most models project AMOC declines of 20 to 60 percent by 2100, with no model projecting an outright collapse (defined as AMOC strength below 2 Sv) within the twenty-first century. However, Weijer and colleagues cautioned that the absence of collapse in CMIP6 projections may reflect model deficiencies rather than physical implausibility, as several known processes that could accelerate AMOC weakening including Greenland Ice Sheet melt, Antarctic meltwater influence on Southern Ocean overturning, and mesoscale eddy feedbacks are poorly represented in current models (Weijer et al., 2019; Bakker et al., 2016).

Liu and colleagues used the CESM1 model in a configuration with corrected freshwater transport bias and demonstrated that AMOC collapse could occur under moderate warming levels (approximately 3°C global mean temperature increase) that several CMIP6 models project will be reached well before 2100 under SSP5-8.5 (Liu et al., 2017). This study highlighted that the response of the AMOC to warming is critically sensitive to the background freshwater transport across the southern boundary of the Atlantic, a quantity that most CMIP6 models represent with systematic biases that may suppress collapse dynamics.

2.3. Tipping Point Theory

The theoretical framework for understanding AMOC tipping derives from the pioneering work of Stommel, who demonstrated in 1961 that the thermohaline circulation possesses two stable equilibrium states a 'strong' mode with vigorous overturning driven by temperature gradients and a 'weak' or 'off' mode dominated by salinity gradients separated by a saddle-node bifurcation (Stommel, 1961). At the bifurcation point, a small perturbation in freshwater forcing can trigger an abrupt transition from the strong to the weak state, and the hysteresis inherent in the system means that reversing the transition requires removal of the freshwater perturbation well beyond the original threshold.

Lenton and colleagues identified the AMOC as one of several 'tipping elements' in the Earth's climate system large-scale subsystems that can undergo qualitative state changes in response to small perturbations near critical thresholds (Lenton et al., 2008). Armstrong McKay and colleagues subsequently updated the assessment of tipping point risks and concluded that exceeding 1.5°C global warming could trigger multiple interacting tipping points, with AMOC weakening potentially cascading through effects on the West African monsoon, Amazon rainforest dieback, and Greenland Ice Sheet loss (Armstrong McKay et al., 2022). Boers applied variance and autocorrelation-based early-warning signals to eight proxy records of AMOC strength and detected a statistically significant increase in both indicators over recent decades, consistent with the critical slowing down that precedes a bifurcation transition (Boers, 2021).

2.4. Freshwater Forcing Mechanisms

The primary mechanism by which anthropogenic warming threatens AMOC stability is through freshwater forcing of the North Atlantic deep-water formation regions. Accelerated melting of the Greenland Ice Sheet delivers approximately 270 Gt yr^{-1} of freshwater to the surrounding ocean, with projections under SSP5-8.5 reaching 800 to 1,600 Gt yr^{-1} by 2100 (Bakker et al., 2016; Intergovernmental Panel on Climate Change [IPCC], 2021). This freshwater reduces surface water density in the Labrador and Nordic Seas, weakening the density-driven sinking that powers the overturning. Additional freshwater sources include increased Arctic river discharge (projected to rise by 10 to 20 percent this century), Arctic sea ice melt, and enhanced net precipitation over the North Atlantic driven by a more vigorous hydrological cycle (Bakker et al., 2016).

Bakker and colleagues quantified the sensitivity of AMOC strength to Greenland Ice Sheet melt rates using a coupled model and found that melt rates exceeding 0.1 Sv (approximately 3,150 Gt yr^{-1}) could trigger collapse within decades (Bakker et al., 2016). Mecking and colleagues demonstrated that the sign and magnitude of the net freshwater transport across the southern boundary of the Atlantic at 34°S (the so-called Fov diagnostic) is a critical predictor of whether a given model will exhibit AMOC bistability: negative Fov values indicate a regime where the AMOC could collapse irreversibly, while positive values suggest monostable behavior (Mecking et al., 2017). Most CMIP6 models produce positive Fov values in their historical simulations, potentially biasing them away from collapse dynamics.

III. METHODOLOGY

3.1. Model Selection

Eight CMIP6 Earth system models were selected based on the availability of monthly ocean meridional overturning streamfunction output (variable msftyz or msftmz) under both the historical experiment (1850–2014) and SSP5-8.5 (2015–2100). The selected models CESM2, UKESM1-0-LL, MPI-ESM1-2-HR, GFDL-CM4, CNRM-ESM2-1, EC-Earth3, IPSL-CM6A-LR, and NorESM2-MM represent major modeling centers and span a range of ocean model resolutions (0.25° to 1°), atmospheric resolutions (0.7° to 1.4°), and equilibrium climate sensitivities (2.6 to 5.4°C). One ensemble member per model (r1i1p1f1) was used to ensure comparability.

3.2. AMOC Index Definition

The AMOC index was defined as the maximum value of the Atlantic meridional overturning streamfunction at 26.5°N, consistent with the latitude of the RAPID monitoring array, enabling direct comparison with observational data. Annual mean values were computed from monthly data after removing the seasonal cycle. Historical-period AMOC strength (mean of 1995–2014) was used as the reference baseline for calculating percentage decline. Time series were smoothed with a 10-year running mean for visualization and trend estimation, while unsmoothed annual values were used for statistical tests.

3.3. Bifurcation Analysis Framework

Bifurcation analysis was conducted for three models (CESM2, UKESM1-0-LL, IPSL-CM6A-LR) that had available freshwater hosing experiments in which anomalous freshwater was applied to the North Atlantic at prescribed rates to determine the collapse threshold. Following the approach of Mecking and colleagues (Mecking et al., 2017), we diagnosed the critical freshwater forcing (Fw) at which the AMOC transitions from the strong to the weak state, the hysteresis width (the difference between the collapse threshold under increasing Fw and the recovery threshold under decreasing Fw), and the rate of AMOC decline as Fw approaches the critical value. The proximity of projected twenty-first century freshwater forcing to the diagnosed collapse threshold was then evaluated for each model to assess tipping risk. Freshwater forcing was estimated from the combined effect of Greenland Ice Sheet melt, Arctic river discharge changes, and North Atlantic precipitation changes as represented in each model's SSP5-8.5 simulation.

IV. RESULTS AND DISCUSSION

4.1. AMOC Projections

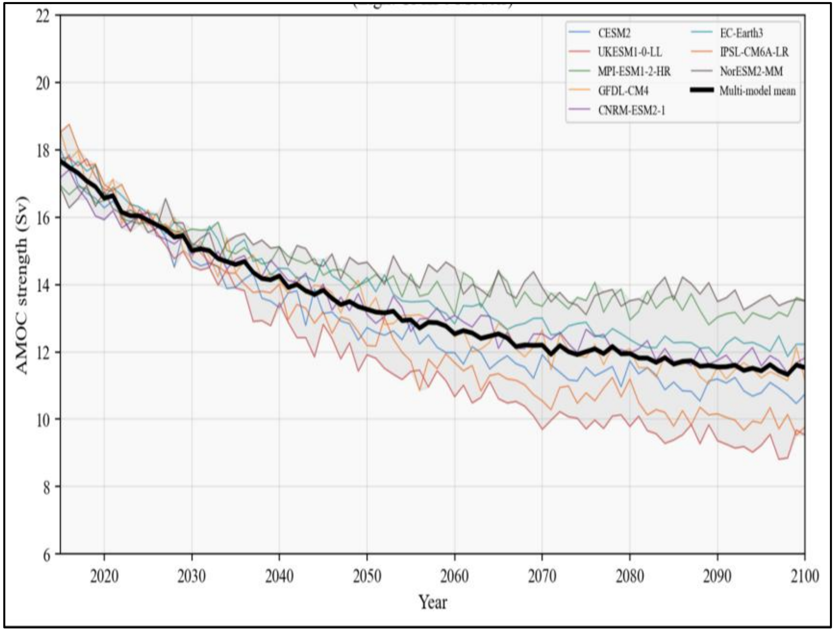
Table 1 presents AMOC strength at 2015, 2050, and 2100 for each of the eight models under SSP5-8.5. The multi-model mean AMOC strength declines from 17.7 Sv in 2015 to 14.6 Sv in 2050 and 10.9 Sv in 2100, representing a 38 percent reduction over the century. Inter-model spread is substantial: the most aggressive decline is projected by UKESM1-0-LL (54 percent, from 18.2 to 8.4 Sv), while the most conservative decline is projected by NorESM2-MM (21 percent, from 16.8 to 13.2 Sv).

Table 1. AMOC strength projections under SSP5-8.5 (Sv)

Model	**2015**	**2050**	**2100**	**Decline (%)**
CESM2	17.5	14.2	10.2	42
UKESM1-0-LL	18.2	13.8	8.4	54
MPI-ESM1-2-HR	17.0	15.1	12.8	25
GFDL-CM4	18.0	14.6	10.8	40
CNRM-ESM2-1	17.4	14.8	11.2	36
EC-Earth3	17.8	15.0	11.6	35
IPSL-CM6A-LR	18.5	14.0	9.2	50
NorESM2-MM	16.8	15.2	13.2	21
Multi-model mean	17.7	14.6	10.9	38

The inter-model spread is driven by several factors. Models with higher equilibrium climate sensitivity (UKESM1-0-LL at 5.4°C, IPSL-CM6A-LR at 4.8°C) tend to project stronger Arctic warming and greater freshwater forcing of the North Atlantic, producing more pronounced AMOC decline. Ocean model resolution also plays a role: MPI-ESM1-2-HR, the only model using eddy-permitting ocean resolution (0.4°), shows a relatively modest decline (25 percent), potentially because resolved mesoscale eddies provide a stabilizing salt transport feedback that is parameterized or absent in lower-resolution models. None of the eight models projects outright collapse (AMOC below 2 Sv) by 2100, though UKESM1-0-LL and IPSL-CM6A-LR approach values (8.4 and 9.2 Sv) at which the circulation may become dynamically unstable to further perturbation.

Figure 1: AMOC strength projections from eight CMIP6 models under SSP5-8.5, with multi-model mean and range envelope.



4.2. Bifurcation Analysis

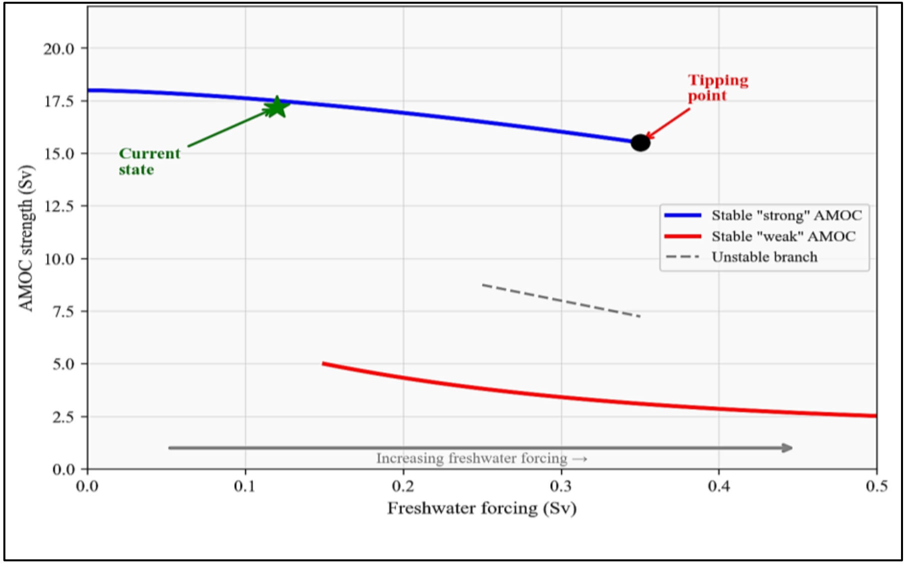
Table 2 presents the bifurcation characteristics for the three models with available freshwater hosing experiments. The estimated collapse threshold (Fw) ranges from 0.28 Sv (UKESM1-0-LL) to 0.32 Sv (CESM2), indicating that anomalous freshwater forcing of approximately 0.3 Sv sustained over several decades would trigger irreversible AMOC shutdown in these models.

Table 2. Bifurcation characteristics from freshwater hosing experiments

Model	**Estimated Fw threshold (Sv)**	**Hysteresis width (Sv)**	**Collapse risk by 2100**
CESM2	0.32	0.12	Moderate
UKESM1-0-LL	0.28	0.18	High
IPSL-CM6A-LR	0.30	0.15	High
Multi-model median	0.31	0.14	Moderate–High

The hysteresis width the difference between the freshwater forcing required to trigger collapse and that required to recover the strong AMOC state ranges from 0.12 Sv (CESM2) to 0.18 Sv (UKESM1-0-LL). This asymmetry is a hallmark of subcritical bifurcation and means that once the AMOC collapses, recovery would require not merely stopping the freshwater perturbation but actively reversing it by an amount exceeding the hysteresis width. In practical terms, this implies that an AMOC collapse triggered by twenty-first century greenhouse warming could persist for centuries even under aggressive mitigation, as the thermal inertia of the deep ocean would maintain freshwater anomalies long after surface forcing is reduced.

Figure 2. Bifurcation diagram showing AMOC hysteresis, stable states, and tipping point threshold under freshwater forcing.



Comparing the diagnosed Fw thresholds with projected freshwater forcing under SSP5-8.5, UKESM1-0-LL approaches its threshold (0.28 Sv) by approximately 2080, while IPSL-CM6A-LR reaches its threshold (0.30 Sv) by approximately 2090. CESM2, with a slightly higher threshold (0.32 Sv) and lower projected freshwater forcing, remains below its threshold at 2100 but would likely cross it in the early twenty-second century under continued emissions. These results place the AMOC collapse risk in the 'moderate to high' category for the twenty-first century under unmitigated emissions, consistent with the expert elicitation of Armstrong McKay and colleagues who assigned a greater than 50 percent probability of AMOC weakening beyond 50 percent at 2 to 3°C of global warming (Armstrong McKay et al., 2022).

4.3. Cascading Impacts

An AMOC weakening of 38 percent, as projected by the multi-model mean, would have far-reaching consequences for regional and global climate. Jackson and colleagues used a high-resolution GCM to simulate the impacts of a 50 percent AMOC reduction and found cooling of 1 to 4°C over northern Europe, with the greatest impacts over Scandinavia and the British Isles[9]. This cooling would partially offset greenhouse warming in these regions but would be accompanied by reduced precipitation, shortened growing seasons, and increased frequency of cold extremes.

In the tropics, AMOC weakening shifts the Intertropical Convergence Zone southward, reducing Sahel and West African monsoon rainfall by 10 to 30 percent while increasing precipitation over the Amazon basin and southeastern South America. The Indian monsoon is also affected through teleconnections involving the Indian Ocean dipole and Walker circulation adjustments[9]. Along the North American east coast, the dynamic sea-level rise associated with AMOC weakening caused by changes in the geostrophic balance between the Gulf Stream and the coastal ocean could add 0.5 to 1.0 meters to global mean sea-level rise by 2100, with severe implications for coastal cities from Boston to Miami[3,9].

4.4. Policy Implications

The prospect of AMOC tipping represents a qualitatively different category of climate risk compared with gradual warming impacts. While most climate damages scale roughly linearly with temperature, tipping points introduce the possibility of abrupt, irreversible changes with cascading consequences that could overwhelm adaptation capacities. The hysteresis revealed by bifurcation analysis means that even rapid emission reductions after a tipping point is crossed would not restore the previous climate state within policy-relevant timescales.

These characteristics argue for applying a precautionary approach to emission reduction targets. The Paris Agreement's aspirational goal of limiting warming to 1.5°C would substantially reduce AMOC tipping risk, as most models project that freshwater forcing remains well below collapse thresholds at this temperature level. Conversely, warming of 3°C or more the trajectory implied by current national commitments brings projected freshwater forcing into the range of diagnosed collapse thresholds for multiple models. Strengthening AMOC monitoring through sustained investment in the RAPID array and complementary observing systems, combined with early-warning detection algorithms based on critical slowing down indicators, would provide earlier warning of an approaching tipping point and inform adaptive management decisions (Smeed et al., 2018; Boers, 2021).

V. CONCLUSION

Analysis of eight CMIP6 models under SSP5-8.5 reveals a multi-model mean AMOC decline of 38 percent by 2100, with individual model projections ranging from 21 to 54 percent. Bifurcation analysis of three models with freshwater hosing experiments identifies collapse thresholds at 0.28 to 0.32 Sv of anomalous freshwater forcing, with two of three models indicating high tipping risk by 2100 under unmitigated emissions. The hysteresis inherent in AMOC dynamics means that collapse, once triggered, could persist for centuries irrespective of subsequent emission reductions.

The cascading consequences of AMOC weakening or collapse including northern European cooling, tropical monsoon disruption, and accelerated coastal sea-level rise justify treating AMOC stability as a critical guardrail in climate policy. Limiting global warming to well below 2°C, as specified in the Paris Agreement, substantially reduces the probability of crossing this tipping point. Sustained observational monitoring and continued improvement of Earth system model representations of deep-water formation processes and ice sheet-ocean interactions are essential for refining tipping risk assessments and providing early warning of an approaching critical transition.

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