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Multi-Stability of the Present-Day Atlantic Meridional Overturning Circulation

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ABSTRACT

The Atlantic Meridional Overturning Circulation (AMOC) plays a key role in the climate system, especially in the global meridional heat transport. Historical reconstructions indicate that the AMOC has weakened by about 15% since the mid-20th century. Paleoclimate records, ocean theory, as well as a hierarchy of climate models suggest that the AMOC is a tipping element, sensitive to changes in buoyancy fluxes at the air-sea interface, and could transition into a substantially weaker or fully collapsed state. Such a transition would have significant climate impacts on decadal to centennial timescales, potentially exceeding societal adaptability. Assessing the probability of such a transition, particularly before 2100, requires evaluating whether a collapsed AMOC state is possible under current forcing conditions. While conceptual and intermediate-complexity models have long identified collapsed states, comprehensive global climate models have only recently done so. Based on integrating model diagnostics with observations and current AMOC theory this review article critically evaluates the current arguments for and against the evidence of a multi-stable AMOC regime. We conclude that the evidence base in favor of such a regime has broadened over the last years and that the present-day AMOC is in such a regime.

This article is categorized under:

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1 | Introduction

The Atlantic Ocean Circulation consists of a complex three-dimensional pattern of currents which are powered by the surface winds, tidal forcing and affected by surface buoyancy fluxes (Ferrari and Wunsch 2009; Cessi 2019). Important features of the circulation are the North Atlantic Current, western boundary currents, such as the Gulf Stream and the Deep Western Boundary Current, which transport specific water masses, such as the North Atlantic Deep Water, throughout the basin. The Atlantic Meridional Overturning Circulation (AMOC) is defined as the zonally integrated volume transport, which can be represented by a meridional overturning streamfunction in depth and latitude (or potential density and latitude), thus providing a two-dimensional view of this circulation. The strength of the AMOC is often characterized by the maximum of this streamfunction at 26° N, typically found at 1000 m depth.

When referring to the "present-day AMOC" in the following, we define it as the state of the AMOC over the past 50 years, specifically from 1970 to 2020. For most of this period, snapshots of the strength of the AMOC can be inferred from in situ observations collected along a limited number of hydrographic sections, which measured temperature, salinity, and pressure throughout the water column (Bryden et al. 2005; Atkinson et al. 2012). Currently, continuous section measurements (Frajka-Williams et al. 2019; Johns et al. 2023; Lozier 2023; Chidichimo et al. 2023) are available at 16° N (MOVE, since 2000), 26° N (RAPID-MOCHA, since 2004), 53°–60° N (OSNAP, since 2014), and at the southern boundary of the Atlantic at 34.5° S (SAMBA, since 2009). At the RAPID-MOCHA section, the mean AMOC strength is about 17 Sv (Frajka-Williams et al. 2019; Johns et al. 2023), where $1\,\mathrm{Sv} = 10^6\ \mathrm{m}^3\mathrm{s}^{-1}$. Here the AMOC transport has decreased by about 4 Sv from 2004 to 2012, while partially recovering thereafter (Moat et al. 2020; Johns et al. 2023). As the observational record is getting longer, it has become clear that there is substantial variability on interannual-to-decadal time scales, which has been discussed at length in two previous review papers (Buckley and Marshall 2016; Jackson et al. 2022). An overall decline has been inferred from proxy data (Rahmstorf 2024), but such a decline has yet to emerge from more direct observations (Johns et al. 2023; Volkov et al. 2024).

While the present-day AMOC is not in strict statistical equilibrium due to transient atmospheric forcing conditions associated with anthropogenic climate change, it is worth noting that achieving such equilibrium is challenging to assess and may not have occurred in any historical period. This is because the AMOC is influenced by millennial-scale climate variability, which can either be driven by or imprints itself on the AMOC. Despite these pronounced long-term variations combined with upward and downward trends over many millennia, there is ample evidence that since the 8.2 Ka event during the late Holocene the AMOC was stable featuring an active "AMOC-on" state characterized by large northward heat transport, similar to what can be observed today (Ayache et al. 2018). In numerical model simulations, a statistically stationary state, characterized by time-invariant statistics, can be achieved by running the models under constant pre-industrial conditions for several thousand years. In models forced by pre-industrial conditions, multi-stability is present if more than one statistical stationary AMOC state is found under the same forcing conditions, starting from different initial conditions (Dijkstra 2024). In this case, the AMOC is said to be in a multi-stable regime. As detailed later, multi-stable regimes have been found in a full hierarchy of models: one state resembles the observed present-day AMOC; the alternative state is characterized by a substantially weakened AMOC, hereafter referred to as "AMOC-off".

The climate research community has mounted a large effort to study tipping phenomena, with the AMOC being a prominent tipping element (Armstrong McKay et al. 2022; Wunderling et al. 2024). Proxy data have provided ample evidence that abrupt transitions between two different equilibrium AMOC states have occurred in the geological past (Lynch-Stieglitz 2016). In particular, transitions between strong and weak AMOC states are likely involved in the well-known millennial time scale changes in Northern Hemisphere temperatures in the last glacial period (Henry et al. 2016), referred to as Dansgaard-Oeschger events (Dansgaard et al. 1993). Proxies, such as high-resolution isotope records from ice cores in Greenland, are used to reconstruct temperature anomalies linked to changes in the meridional heat transport by the AMOC (Rahmstorf 2002). With large ice sheets and extended sea ice, the glacial climate was distinctly different from the present climate. From the paleoclimatic records it cannot be concluded that the present-day AMOC is in a multi-stable regime. This uncertainty has led to skepticism within the scientific climate community about a possible onset of abrupt weakening of the AMOC during the 21st century (Gent 2018; Volkov et al. 2024).

A strong reduction in the AMOC strength is often called a collapse. AMOC weakening can be 'forcing dominant' due to an imposed forcing or it can be 'feedback dominant' because external conditions exceed a certain threshold. For example, for typical freshwater pulse forcing simulations in Orihuela-Pinto et al. (2022), the AMOC change (in Sv) per cumulative change in North Atlantic freshwater forcing (1 Sv/year over a 50-year period) is about 0.36 year^{-1}, indicating that the forcing dominates in the AMOC weakening. On the contrary, this factor is about 5.3 year^{-1} for the quasi-equilibrium simulations in van Westen et al. (2024), indicating that the AMOC weakening is due to a crossing of critical conditions and dominantly caused by a positive feedback. In this case, it is also transitioning to a different statistical equilibrium and there is hysteresis and irreversibility when the forcing is reversed (van Westen and Dijkstra 2023). Alternatively, using water mass transformation theory, it could be said that the AMOC has collapsed when the adiabatic contribution to the AMOC for density classes larger than that of the lightest North Atlantic Deep Water approaches zero (Wolfe and Cessi 2015; van Westen, Vanderborght, et al. 2025). In this case, there are no adiabatic pathways anymore that link the Atlantic to the Southern Ocean, but still a weak AMOC strength can result through 'non-local' influences from the Southern Ocean and the Indo-Pacific basins (Baker et al. 2025). These examples illustrate the importance of working towards a widely agreed set of terminology of an AMOC collapse that is both scientifically

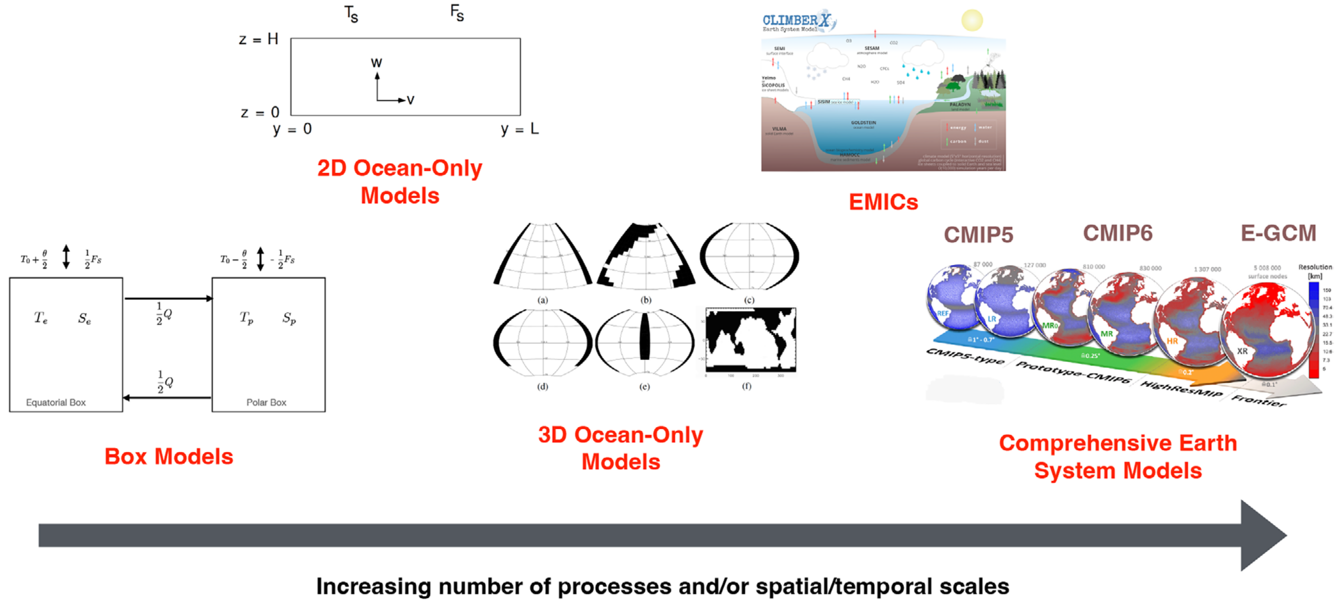

FIGURE 1 | AMOC model hierarchy, going from Box Models at the left to Comprehensive Earth System Models (CMIP5-CMIP6-E-GCM) to the right. Here E-GCM indicates the top level of the hierarchy, with ocean components that resolve ocean eddies.

precise enough, and allows meaningful communication on the issues with non-specialist audiences.

The aim of this paper is to provide a critical overview of the arguments for and against the evidence that the present-day AMOC is in a multi-stable regime. The paper is motivated by the attention given by the press, policymakers, and the general public to the possibility of an imminent collapse of the present-day AMOC, which could have disruptive impacts on society (Rahmstorf 2024). The multi-stability of the AMOC, or its absence, influences the likelihood of its collapse under climate change and informs the development of early warning systems for potential AMOC collapse. Further, with increasing interest in the possibility of temporarily overshooting climate targets, it is important to understand whether an overshoot could cause AMOC changes that are effectively irreversible when global temperatures are eventually restored to their target value. In the following, the previous review paper by Weijer et al. (2019) is extended and updated with recent results on the stability of the AMOC. Additionally, some of the open issues posed in Weijer et al. (2019) are addressed, in particular the identification of an AMOC collapse in Earth System Models and the usefulness of previously proposed indicators of AMOC stability.

2 | Multi-Stability of the AMOC

2.1 | The AMOC Model Hierarchy

To discuss the AMOC-MS issue, it is useful to base the hierarchy of models on two main characteristics: scale-resolution (spatial and temporal) and included processes (Dijkstra 2013). At the lowest level in the hierarchy (Figure 1) are ocean box-models, for example, the original Stommel two-box model (Stommel 1961). These models have a small number of degrees of freedom (i.e., few dependent variables) and few control parameters representing simplified processes with idealized spatial and temporal interactions.

Proceeding upwards in the hierarchy, are spatially extended one-dimensional, two-dimensional, and three-dimensional ocean-only models with idealized geometries. Examples in this category are ocean models in a spherical sector or with the Atlantic sector coupled to a southern channel. Further upwards in the hierarchy are global ocean-only models, such as POP (EMICs, Smith et al. 2000) and Earth System Models of Intermediate Complexity (Claussen 2002), such as ClimberX (Willeit et al. 2022). The latter category includes an idealized global ocean component coupled to idealized land, ice, and atmosphere models.

At the penultimate level of the hierarchy are global climate models, for example, the CMIP5 and CMIP6 models. At this level, the spatial resolution of the ocean component in most models does not allow to resolve processes at the mesoscale, such as ocean eddies, so these processes are parameterized. The top level of the hierarchy (labeled here as E-GCM) consists of state-of-the-art models, either only physics based (e.g., ICON (Jungclaus et al. 2022)) or hybrid, including data-based components (Kochkov et al. 2024), which resolve the ocean eddies and many more processes. Recent improvements in available compute power has enabled the ability to look at the AMOC in models at even higher resolution (up-to 0.05°) (Hirschi et al. 2020). However, the expense of running these simulations and storing the data prohibits experiments of several 100 years.

2.2 | AMOC Multi-Stability: The Salt-Advection Feedback

The paradigm of a multi-stable AMOC regime was established by the Stommel two-box model (Stommel 1961). In this configuration, properties are well-mixed in each box. The boxes are connected by two hydraulic links, one in the upper ocean and one in the deep ocean, and the density depends linearly on temperature and salinity of the boxes. The temperature and salinity in each box are determined by heat and salt exchanges between the two boxes, with a strength proportional to the (meridional) density difference between the boxes. The model also includes heat exchange with the atmosphere and a freshwater flux (representing precipitation, evaporation, river runoff and ice melt).

Because the temperature adjustment is much faster than the salinity adjustment, the temperature difference between the boxes is fixed. The MS regime is controlled by the freshwater flux parameter (Cessi 1994) giving the archetypal bifurcation diagram as in Figure 2. In such a bifurcation diagram, a measure of the steady states in the model, here the AMOC strength, is plotted versus a parameter (here the freshwater-flux strength). The MS regime is bounded by two saddle-node bifurcation points, L_1 and L_2 in Figure 2. In this regime, two steady AMOC states (black solid curves in Figure 2) are stable and one is unstable (dashed).

When the two-box model is integrated in time with a freshwater flux that linearly increases in time, on a time scale much slower than the restoring rate for the salinity, the AMOC strength stays close to one steady state for quite a while, but when L_1 is crossed a collapse occurs. When the freshwater flux is decreased at the same rate as the linear increase, a recovery of the AMOC occurs when the threshold L_2 is passed (blue curves in Figure 2). This hysteresis under a quasi-equilibrium (i.e., slow) transient change of the freshwater flux is a key signature of the AMOC-MS regime.

From the transient simulations of the two-box model, the physical mechanism of the AMOC collapse can be understood: In the “AMOC-on” state, the density in the polar box is much higher than in the equatorial box, sustaining a strong AMOC. When a freshwater perturbation is applied in the polar box, the polar density decreases and the AMOC weakens. This decreases the poleward heat and salinity transport by the AMOC and, while temperature anomalies are damped by the atmosphere, salinity anomalies are hardly affected. Hence, the decreased salinity transport will further freshen the polar box, leading to a further decrease in the AMOC. This positive feedback is called the salt-advection feedback (SAF) (Stommel 1961; Marotzke 2000).

By tracking steady states with direct computations, bifurcation diagrams such as those in Figure 2 have been calculated for low-resolution ocean-only models up to the global scale (Dijkstra 2007). These models include complex ocean geometry, a relatively viscous wind-driven ocean circulation and, despite the large diapycnal diffusivity, capture the nonlinear coupling between buoyancy transport and the AMOC, and thus the SAF. It is therefore not surprising that bifurcation diagrams similar to Figure 2 are found (Dijkstra 2007). Unlike the two-box model, the global ocean configuration gives the spatial patterns of the circulation and property distributions, enabling a more detailed analysis of the processes controlling the AMOC-MS regime.

With global ocean-only models and EMICs, quasi-equilibrium simulations have been performed and hysteresis has been found, indicating the existence of AMOC-MS regimes (Lohmann et al. 2024). The range of freshwater forcing strengths for which this regime exists is model and parameter dependent in EMICs (Rahmstorf et al. 2005) and also depends on the rate of change in the freshwater forcing. When rates are faster than the adjustment time scale of the AMOC under freshwater changes, there is no quasi-equilibrium anymore and overshoot phenomena can occur. Consequently, the parameter values where collapse and recovery are found do not correspond anymore to the saddle-node bifurcations (Berglund and Gentz 2006; Ritchie et al. 2021).

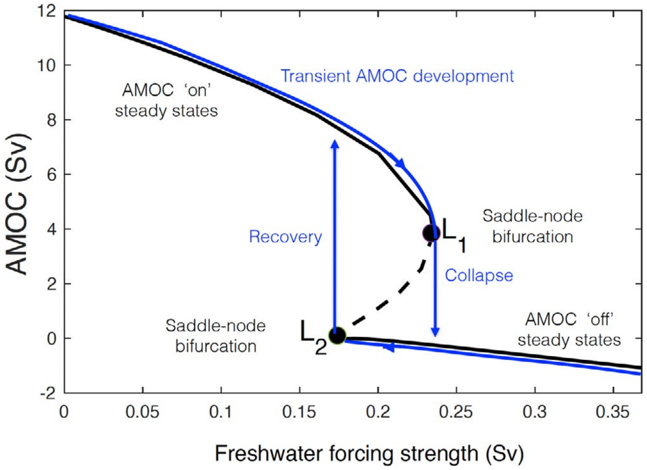

FIGURE 2 | Bifurcation diagram (black curves) of the Cessi (1994) model showing the AMOC strength versus the freshwater forcing strength (both in Sv). Solid (dashed) curves represent stable (unstable) steady states. In a quasi-equilibrium simulation (blue curves), the trajectory undergoes a collapse and recovery near the saddle-node bifurcations L_1 and L_2, respectively.

Several quasi-equilibrium simulations have been performed with CMIP3-generation models, in particular FAMOUS (Hawkins et al. 2011) and CCSM4 (Hu et al. 2012). The FAMOUS simulations have explicitly shown that an AMOC-MS regime exists with a strong “AMOC-on” state coexisting (i.e., can be reached from different initial conditions) with a weak “AMOC-off” state. In CCSM4, hysteresis of the AMOC strength exists both with and without opening of the Bering Strait (Hu et al. 2012), but the width is smaller when it is open. Due to the high computational costs, a quasi-equilibrium simulation with a CMIP5 model (the CESM1) has only recently been performed (van Westen and Dijkstra 2023). This CESM1 simulation starts with a pre-industrial equilibrium climate. Then, the freshwater flux, characterized by a magnitude F_H, is slowly increased over a region in the North Atlantic (inset in Figure 3a with a magnitude F_H in Sv). A collapse is found to occur at $F_H \sim 0.5$ Sv. When subsequently the freshwater flux perturbation is slowly decreased, a recovery occurs at $F_H \sim 0.1$ Sv, thus revealing a substantial range of F_H where hysteresis is found ($\sim$0.4 Sv). The values of F_H for both collapse and recovery are very high compared to present-day meltwater discharge from the Greenland Ice Sheet, but note that the additional buoyancy forcing of the AMOC by global warming is not included here.

Simulations in which an AMOC equilibrium is perturbed by a relatively strong freshwater forcing, either in initial conditions for salinity or in the freshwater flux, have been performed with CMIP3, CMIP5, and CMIP6 models. Although the integration

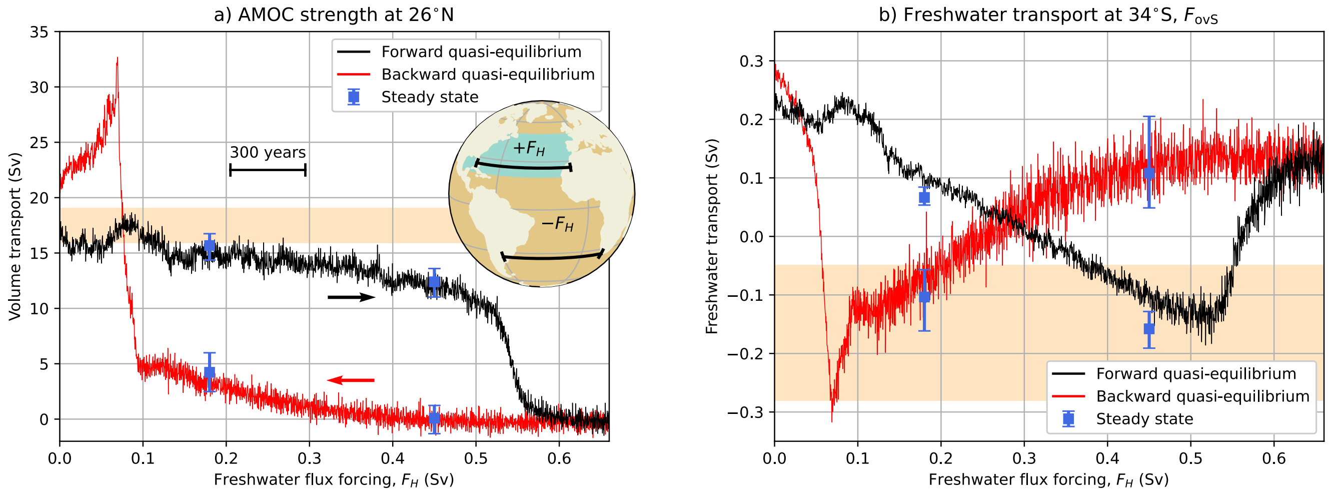

FIGURE 3 | (a) The AMOC strength at 1000 m and 26° N versus the freshwater forcing F_H. Several statistical equilibria (i.e., steady states in dark blue) are also shown, where the marker indicates the mean and the error bars show the minimum and maximum over the last 50 years of the 500-year long branched simulations. Inset: The cyan region indicates where fresh water is added to the ocean surface, between 20° N—50° N in the Atlantic Ocean ($+F_H$) and it is compensated over the remaining global ocean surface ($-F_H$). The black sections indicate the 26° N and 34° S latitudes over which the AMOC strength and F_{ovS} are determined, respectively. (b) The freshwater transport by the AMOC at 34° S, indicated by F_{ovS}. Ranges from observations are indicated by the yellow shading (Smeed et al. 2018; Worthington et al. 2021; Garzoli et al. 2013; Arumí-Planas et al. 2024).

time of these simulations is rather short (a few hundred years), indications for collapsed AMOC states and for hysteresis have been found in these as well (Orihuela-Pinto et al. 2022; Jackson and Wood 2018a, 2018b; Jackson, Alastrué de Asenjo, et al. 2023). In summary, an AMOC-MS regime has been found in a large part of the model hierarchy (up to CMIP5), and indications for stable "AMOC-off" states have been found even in eddy-permitting models (Mecking et al. 2016) and strongly-eddying models (Van Westen et al. 2025).

2.3 | Diagnostics of the SAF: F_{ovS}

Because models at the top of the hierarchy capture many more processes and scales than simpler models, it is important to have a quantitative diagnostic of the SAF (its strength and sign) in the spatially extended, most complex context. The SAF is the major feedback controlling the AMOC-MS in models for which bifurcation diagrams can be computed explicitly (i.e., ocean-only models in the lower part of the hierarchy). In more complex models, such as climate models in the CMIP class, other feedbacks will play a role in the AMOC stability (see Section 2.4). The question is whether the stabilizing feedbacks of the more complex models are strong enough to oppose the SAF.

A pole-to-pole variant of the Stommel model that includes flow into the Antarctic Circumpolar Current (ACC), where the AMOC is proportional the north–south density difference, illustrates that the bifurcation point L_2 (cf. Figure 2) is determined by a sign change of the freshwater transport carried by the AMOC out of the Atlantic (Rahmstorf 1996). In addition, L_1 (cf. Figure 2) is determined by a negative minimum of this net freshwater export. The implication is that the MS regime exists only when the AMOC exports freshwater out of the basin (or imports salinity into the basin). It has been shown in an EMIC that the sign of this freshwater transport, whose amplitude is largest at the southern boundary of the Atlantic, is associated with the stability of the AMOC (de Vries and Weber 2005; Sijp 2012; Sijp et al. 2012). The same result holds in global ocean-only models (Dijkstra 2007) where a negative freshwater transport divergence by the AMOC, with the largest transport at the southern boundary, also characterizes the MS regime of the AMOC. The freshwater transport by the AMOC was originally denoted by M_{ov} (de Vries and Weber 2005), but here Hawkins et al. (2011) and Weijer et al. (2019) are followed and we will use F_{ov}. The value of F_{ov} at the southern boundary of the Atlantic, 34° S, is denoted by F_{ovS}.

Although only a few equilibrium simulations were performed, the MS regime in the FAMOUS model also appears to be characterized by a negative F_{ovS} (Hawkins et al. 2011). In the coupled CESM quasi-equilibrium simulations where the freshwater flux is slowly changed, F_{ovS} goes through a minimum just before the AMOC collapses (figure 3b and van Westen et al. 2024). While in simpler models the MS regime exists only for $F_{ovS} < 0$ (Dijkstra 2007), in CESM the MS regime extends from negative to positive values of F_{ovS}. Equilibrium simulations of the CESM, where the freshwater flux is fixed, and the initial condition is taken from transient states in quasi-equilibrium simulations, also exhibit multiple statistical equilibria, both for $F_{ovS} < 0$ and $F_{ovS} > 0$ (Figure 3b).

The connection between the SAF and F_{ovS} was analyzed in detail using the quasi-equilibrium CESM simulation, by reconstructing the AMOC from the buoyancy field and analyzing all feedbacks involved in the AMOC collapse (Vanderborght et al. 2025). The overturning salt-advection feedback is the dominant destabilizing mechanism and is responsible for the AMOC collapse. The SAF response can be measured by the F_{ovS} sign: when $F_{ovS} < 0$, the SAF destabilizes the AMOC and the opposite is true for $F_{ovS} > 0$, while the strength of the SAF scales with F_{ovS}. This is in agreement with model results where a different AMOC response under climate change (Liu et al. 2017) is found when the "AMOC-on" state has a different sign of F_{ovS}.

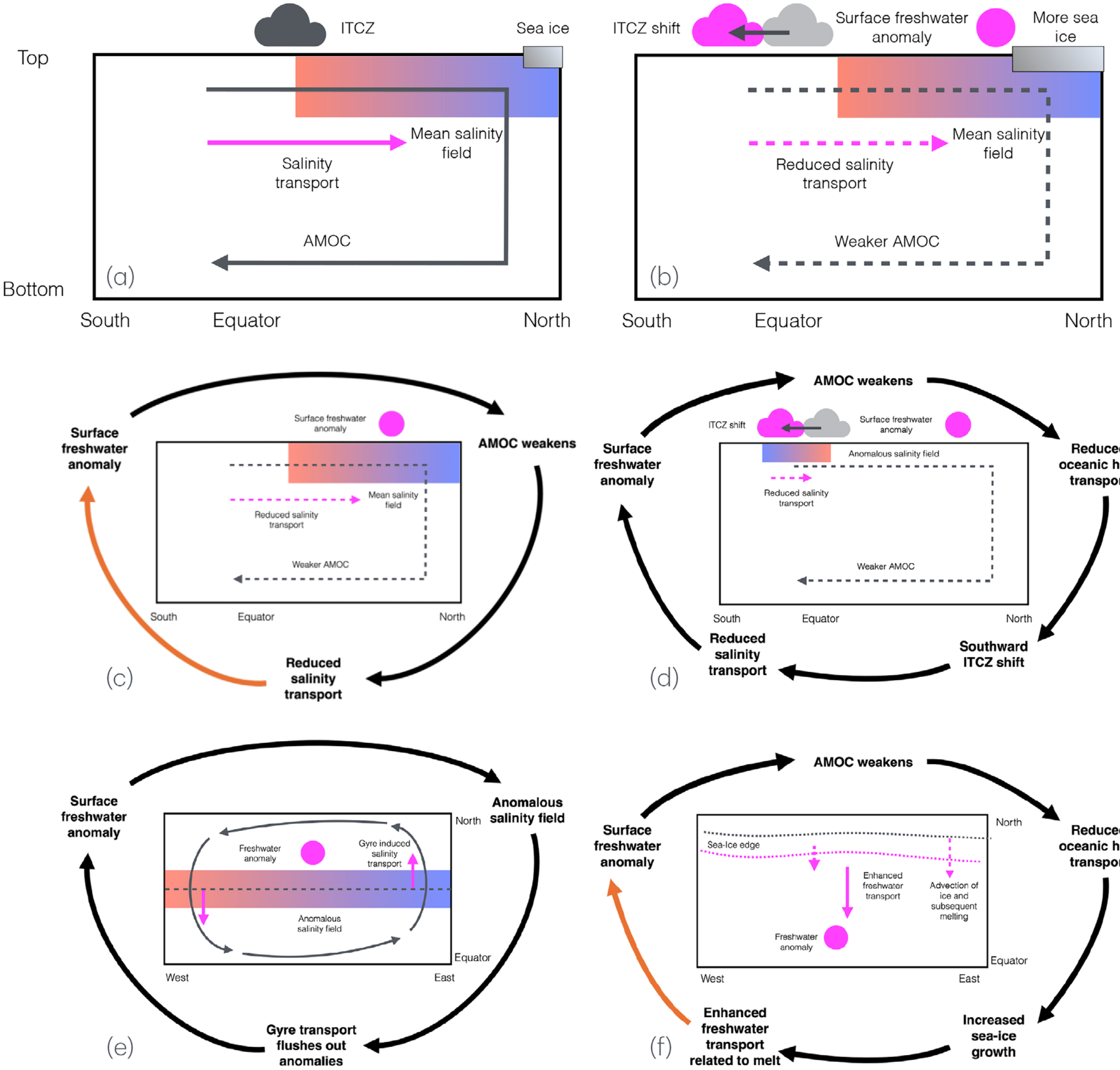

FIGURE 4 | Sketch of the different processes and feedbacks involved in the AMOC collapse. (a) 'Normal' background case without a freshwater anomaly, (b) Changes in the climate following a freshwater anomaly, (c) Salt advection feedback, (d) Atmosphere-AMOC feedback, (e) Gyre feedback, and (f): Sea ice-AMOC feedback. The gradient color rectangles indicate the background salinity field in (a) to (c) and the anomalous salinity field in (d) and (e), with red (blue) indicating high (low) salinity. The magenta dots (drawn arrows) indicate freshwater anomalies (transport). Orange arrows in the feedback loops represent a positive feedback.

2.4 | Additional Relevant Feedbacks

A sketch of the different feedbacks is provided in Figure 4, with Figure 4a describing the 'normal' background state and Figure 4b the changes following a freshwater anomaly. The mechanism of the SAF is sketched in Figure 4c where a freshwater anomaly over a certain region in the northern North Atlantic will lead to an AMOC weakening. If the AMOC exports freshwater from the Atlantic, the Atlantic basin becomes fresher due to the AMOC weakening, amplifying the original perturbation. Apart from the SAF, there are other feedbacks (both positive and negative) which control the equilibrium AMOC response to surface freshwater forcing changes. Of these, the feedback due to freshwater transport by the gyres is amply discussed in Weijer et al. (2019). Given a freshwater anomaly that could lead to an AMOC weakening, the wind-driven gyres can transport freshwater into (or out of) the freshwater anomaly region leading to a positive (or negative) gyre feedback (Figure 4e), often connected to the azonal freshwater transport F_{az}. This process occurs even if the changes in the surface wind-stress due to the AMOC changes are excluded: transporting heat and fresh water is a simple kinematic property of the wind-driven gyres.

An AMOC weakening also affects the surface freshwater fluxes. For example, the global Earth heat budget requires that the reduction in poleward heat transport by the AMOC is replaced by an equivalent heat transport by the atmosphere associated with the position of the Hadley cells or by changes in the atmospheric radiation budget (Vellinga and Wu 2008). The net result of AMOC weakening is a southward shift (Figure 4d) of the InterTropical Convergence Zone (ITCZ). In turn, the ITCZ shift changes the precipitation patterns and the associated freshwater fluxes leading to an atmosphere-AMOC feedback (Stouffer et al. 2006; Kang et al. 2008). Furthermore, the shift in ITCZ leads to a salinification of the subtropical North Atlantic which can act to destabilize an "AMOC-off" state if not counteracted by advection of salinity (Stouffer et al. 2006). Transport of freshwater through the Bering Strait has also been shown to be important for the overall AMOC stability (Hu et al. 2007), with a closure of the Bering Strait in general stabilizing the AMOC. A relevant feedback is associated with sea-ice processes, where a weakening of the AMOC causes an increase in Arctic sea-ice extent near the Greenland coast in winter (Liu and Fedorov 2022). The surface flow from the Arctic to the Atlantic (i.e., the East Greenland current) advects the additional sea ice towards the North Atlantic region during the following summer, leading to an enhanced freshwater flux over the anomaly region (Figure 4f), causing a positive sea ice-AMOC feedback. A weaker AMOC also leads to more sea ice growth that, through brine rejection, acts as a negative feedback on the AMOC (Liu and Fedorov 2022).

In the quasi-equilibrium CESM simulation, the sea ice-AMOC feedback and the atmosphere-AMOC feedback destabilize the AMOC (Vanderborght et al. 2025). The gyre circulation plays a key role in stabilizing the AMOC, with the subpolar gyre feedback in the North Atlantic providing the primary stabilization effect while the subtropical gyre feedback in the South Atlantic is destabilizing. The difference between these two gyre feedback effects determines the degree of AMOC stabilization by the wind-driven salinity transport. However, all those stabilizing feedbacks are eventually smaller in the CESM than the SAF, leading eventually to an AMOC collapse under increasing freshwater forcing.

It is expected that the strength of these feedbacks is model dependent (Goes et al. 2019) and that their relative importance may also change once ocean eddies are represented. In eddy-permitting (Mecking et al. 2016) and strongly-eddying ocean models (Toom et al. 2014), the Atlantic freshwater balance is quite influenced by eddy-transport, which will affect the strengths of the gyre feedback (Jüling et al. 2020). The sensitivity of sea-ice extent to changes in the AMOC is expected to be strongly model dependent (Lin et al. 2023). Also, more detailed atmospheric models will change the surface freshwater flux response to AMOC changes, affecting the strength of the atmosphere-AMOC feedback. There are several other feedbacks; for example, the effect of AMOC weakening on the Atlantic jet stream and storm track, which affects the northward Ekman transport, but these are not further considered.

2.5 | Arguments for and Against AMOC-MS

One of the main arguments in favor of a present-day AMOC-MS is that this regime is found in a large range of models of the hierarchy (Weijer et al. 2019). Further support comes from CMIP3 and CMIP5 models, extending the range of complexity where AMOC-MS is found. Testing AMOC-MS, even in the lower resolution versions of CMIP6 models could in principle be done now, but at substantial computational cost. Testing AMOC-MS in CMIP5-type models with an eddy-resolving ocean component is even more costly and probably not doable soon. However, results from a model in an idealized geometry that includes wind-driven gyres and eddy-parametrizations, with very weak diapycnal diffusion, that is, in the quasi-adiabatic regime expected for eddy-resolving models, reassure that an AMOC-MS should be robust to increase in model resolution (Wolfe and Cessi 2015). Indeed, very recently an AMOC collapse and indications for an AMOC-MS, have been determined in a strongly-eddying global ocean model (Van Westen et al. 2025).

When the northward AMOC overturning is in the AMOC-MS regime, simplified models, that is, in the lower part of the hierarchy, have a negative value of F_{ovS} (Dijkstra 2007; Huisman et al. 2010). While analyses of CESM clearly reveal that F_{ovS} reflects the strength of the SAF, its reliability as a quantitative indicator of a AMOC-MS regime in climate models remains uncertain (Vanderborght et al. 2025). For example, in CESM, the "AMOC-off" state is stabilized by the southward expansion of Arctic sea ice, even when F_{ovS} is positive for the "AMOC-on" state (van Westen and Dijkstra 2023). This result demonstrates that other feedback mechanisms, such as gyre and sea-ice feedbacks, play a significant role in the Atlantic freshwater budget. Based on the results of Cimatoribus et al. (2014), F_{ovS} is a reliable indicator for multiple equilibria only if other feedbacks are negligible compared to the SAF. There may also be regions in parameter space where a single equilibrium exists and yet $F_{\mathrm{ovS}} < 0$. Model results indicate that the range of parameters where this behavior is found is small and the magnitude of F_{ovS} is near zero (Dijkstra 2007; Cimatoribus et al. 2014).

The time series of observed data in the South Atlantic is relatively short (around 20 years for the longest time series). However, from these data, it is clear that $F_{\mathrm{ovS}} < 0$ (Figure 5). A recent analysis of the different AX18-XBT transects at nominally 34.5° S in the Atlantic Ocean gives an estimate for F_{ovS} of -0.15 ± 0.09 Sv (2002–2019) (Arumí-Planas et al. 2024). This estimate is in agreement, within uncertainty, with results from hydrographic and Argo float data at similar latitudes (Bryden et al. 2011; Garzoli et al. 2013; Arumí-Planas et al. 2024; Caínzos et al. 2022; Weijer et al. 1999; Huisman et al. 2010; Pita et al. 2024) and with models that assimilate these data sets (Rousselet et al. 2020; van Westen et al. 2024). Clearly, the AMOC exports freshwater out of the Atlantic basin, which leads to a destabilizing SAF. The mean observed values are also sufficiently negative that an AMOC-MS regime is expected.

The quantity $\Sigma = F_{\mathrm{ovS}} - F_{\mathrm{ovN}}$ (also referred to as ΔF_{ov}) has been proposed as a better stability indicator than F_{ovS}, where F_{ovN} is evaluated at the northern boundary of the Atlantic (Dijkstra 2007; Huisman et al. 2010; Liu et al. 2017). Evaluating F_{ovN} at the boundary between the Arctic and the North Atlantic assumes that the freshwater budget of the Arctic is operating independently of the Atlantic. Alternatively, if the Arctic freshwater budget is tightly coupled to the subpolar North Atlantic freshwater budget, then the Arctic circulation participates in the AMOC. In this case, the relevant F_{ovN} should be evaluated at the Bering Strait, where it is very small. At the moment, no

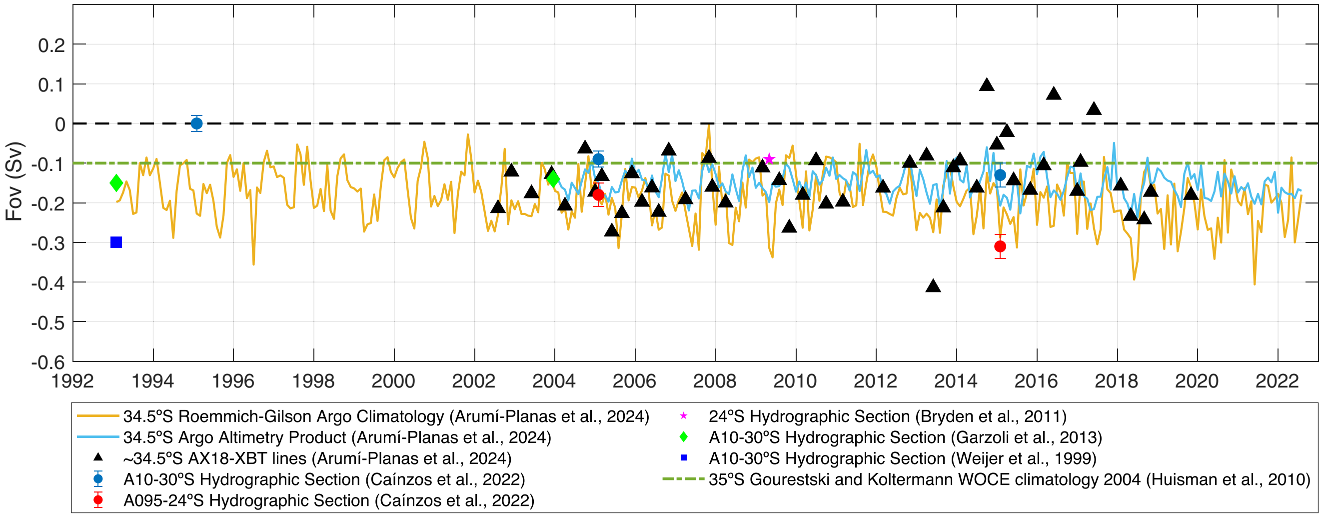

FIGURE 5 | Observational data employed until now (Arumí-Planas et al. 2024) to compute F_{ov} in the South Atlantic Ocean along latitudes 24°S, 30°S and 35°S. The legend indicates the latitude, the different sources of observational data, and the bibliographic citation for each F_{ov} calculation. The black dashed line represents $F_{\mathrm{ov}} = 0$, emphasizing that most values are negative.

observation-based estimates have been made of F_{ovN}. As suggested by Dijkstra (2007) it may be worth attempting to evaluate this indicator, especially now that observations further north are available, for example, the OSNAP array, (Frajka-Williams et al. 2019; Lozier 2023).

The main counterargument on the use of F_{ovS} as AMOC stability indicator is the possible stabilizing effects of other processes due to AMOC changes, in particular the wind-driven gyres. For example, Gent (2018) considers the differences in Atlantic freshwater divergences due to overturning and gyres in the Mecking et al. (2016) simulations, where a large freshwater perturbation is added in the HadGEM3 model (10 Sv for 10 years in an ocean-only model at 0.25° horizontal resolution). The changes in both overturning and gyre transports are indeed comparable, but the analysis (Vanderborght et al. 2025) of the CESM simulation shown in Figure 3, where an AMOC collapse is found under slowly changing conditions, shows that it is the difference in the divergences of the gyre freshwater transport which matters, not the values of these transports themselves. This adds a nuance to the argument in Weijer et al. (2019) that the gyres do not control the stability of the AMOC; instead the AMOC stability depends on the net effect of stabilizing and destabilizing gyre feedbacks.

Recent studies on internal variability in CMIP5 models indicate that there are no significant effects of South Atlantic freshwater transport anomalies on AMOC strength under statistically stationary conditions (Haines et al. 2022; Cheng et al. 2018; Mignac et al. 2019). However, even if the AMOC were monostable, it would have internal variability on interannual-to-multicentennial time scales, which is controlled by processes different from those involved in an AMOC collapse. The results in Vanderborght et al. (2025) also show signatures of internal variability, but the buoyancy anomalies involved remain restricted to the North Atlantic. Hence, no response in freshwater transport at the Atlantic's southern boundary is found. As a consequence, F_{ovS} is only a robust measure of AMOC stability under (quasi-)equilibrium conditions, that is, when the cross-hemispherical component of the AMOC has had time to adjust. Under rapid climate change or large freshwater perturbations, F_{ovS} may not be a good indicator of transient AMOC changes. Indeed, even though their simulations are short, in the NAHosMIP pulse forcing simulations (Jackson, Alastrué de Asenjo, et al. 2023) the F_{ovS} sign in the control experiment does not appear to be connected to AMOC recovery or weak state approach.

3 | Consequences of AMOC-MS

3.1 | Model Biases

The diversity of AMOC behaviors in the CMIP3, CMIP5 and CMIP6 pre-industrial, historical and climate change scenario simulations is not surprising given the many feedbacks controlling the AMOC response to a changing atmosphere. Indeed, the mean AMOC strength has a wide range of values even under pre-industrial conditions. Most models show an increase of the AMOC in the late 20th Century and a decay of the AMOC ranging from 2–10 Sv under climate change scenarios up to the year 2100 (Weijer et al. 2020).

Analysis of CMIP3 (Drijfhout et al. 2011) and CMIP5 (Mecking et al. 2016) models have shown that positive values of F_{ovS} of the present-day AMOC were mostly caused by biases in the freshwater flux over the South Atlantic. The systematic assessment of CMIP6 model biases affecting the SAF have shown that freshwater flux biases in the Indian Ocean and northern North Atlantic cause a positive F_{ovS} in many models (Van Westen and Dijkstra 2024). For example, excessive precipitation over the Indian Ocean leads to a negative salinity bias. This salinity anomaly is transported northward across the southern boundary of the Atlantic. In turn, this leads to an anomalous freshwater import causing the positive F_{ovS} bias (Van Westen and Dijkstra 2024). Additionally, the climatological values of salinity deviate from observational estimates. At 34° S, the different water masses over the vertical deviate from observations as well: the southward flowing North Atlantic

Deep Water is too salty, while the northward flowing Atlantic Surface Water is too fresh.

In a global ocean-only model (Dijkstra 2007), the effect of this Indian Ocean freshwater bias on the AMOC-MS is to shift the saddle-node bifurcations (Figure 6) to higher North Atlantic freshwater forcing (Dijkstra and van Westen 2024). Similar behavior was found in the EMIC CLIMBER-X (Boot and Dijkstra 2025). This shift occurs because a larger North Atlantic freshwater forcing is needed to activate the SAF. Note that in more extended models, the Indian Ocean can also affect the AMOC stability through atmospheric feedbacks (Hu and Fedorov 2020), not considered in Dijkstra and van Westen et al. (2024).

If such shifts would also occur in CMIP6 models, this result suggests that model-biases require parameter values outside the realistic range in order to simulate the present-day AMOC-MS regime. In other words, the CMIP6 model biases may erroneously place the present-day "AMOC-on" state in the single equilibrium part of the AMOC-MS regime (as indicated by the red star in Figure 6). This may be the origin of the large range of behaviors between models in the NAHosMIP results, where 0.3 Sv is for only half of the models enough to induce a temporary weak state (Jackson, Alastrué de Asenjo, et al. 2023). Biases leading to modifications of other feedbacks, for example, those involving sea ice, are also expected to shift the AMOC-MS regime, but the magnitude and sign of these shifts is yet to be investigated.

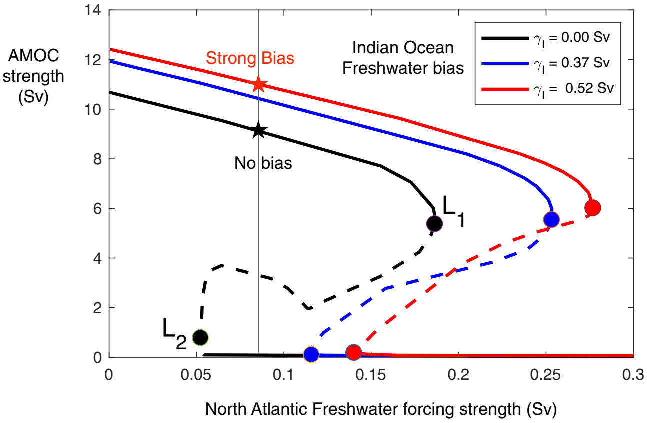

FIGURE 6 | Effect of Indian Ocean precipitation biases on the range of Atlantic freshwater fluxes exhibiting hysteresis in a global ocean-only model (Dijkstra and van Westen 2024). Here, γ_I measures the strength of the freshwater bias and on the x-axis the strength of the North Atlantic freshwater forcing is shown. The North Atlantic freshwater flux anomaly is compensated by a uniform anomaly of the opposite sign distributed in the rest of the global domain.

3.2 | Transient Behavior

The existence of AMOC-MS has profound consequences for the possible future AMOC transient behavior under climate change scenarios. Increase in greenhouse gasses mostly affects the surface heat fluxes through changes in the radiation balance. In turn, the temperature changes induce surface freshwater flux anomalies through changes in sea-ice/land-ice and in evaporation/precipitation/runoff.

MS can lead to three types of tipping phenomena, involving a large AMOC response in the AMOC due to the changes in the atmospheric forcing (Figure 7). Firstly, with reference to Figure 2, the bifurcation point L_1 can be crossed as the atmospheric forcing changes in time, leading to bifurcation tipping and AMOC collapse. Secondly, the rate of change of the atmospheric forcing can be so fast that a rate-induced tipping occurs before the forcing actually reaches the value at L_1 (Ashwin et al. 2012). Several box models, EMICs and ocean-only models have been shown to display such a transition (Lohmann et al. 2021; Stocker and Schmittner 1997; Lohmann and Ditlevsen 2021). Finally, a "noise-induced transition" can occur (Cini et al. 2024). In this third case, the present-day AMOC can undergo a rapid transition caused by internal variability associated with smaller scale processes (i.e., the 'noise').

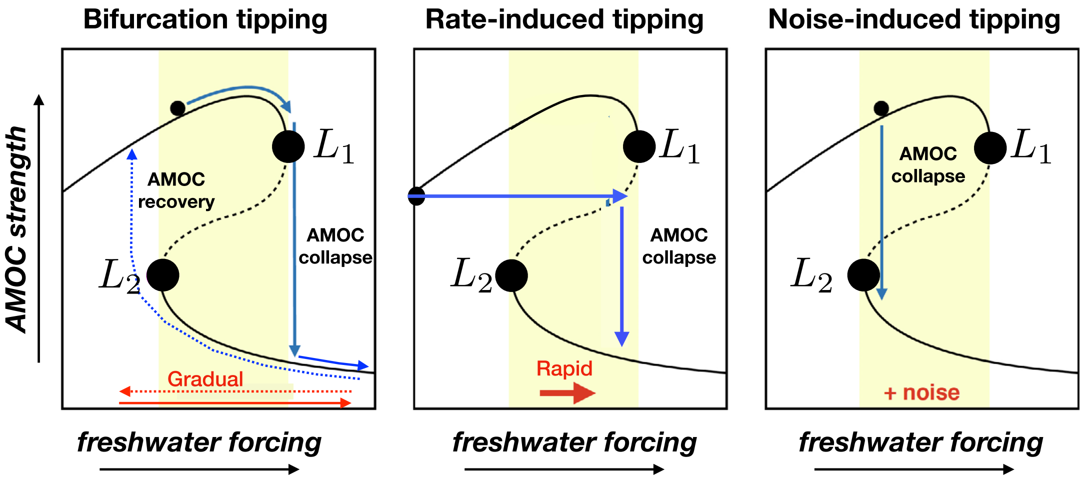

FIGURE 7 | Different types of transient behavior due to bifurcation tipping, rate-induced tipping and noise-induced tipping. The large black dots indicate the saddle-node bifurcations, the small dots indicate the initial state of the AMOC, the red arrows the changes in freshwater forcing and the blue curves the different transition pathways. The yellow shading indicates the multiple equilibrium regime.

The transient-forcing scenario can be viewed as the process of moving the equilibrium bifurcation diagram of Figure 2 in time to the left or right (Ritchie et al. 2021). In this case, the actual AMOC state can move through different regimes (either multistable or not). The timescale on which the AMOC responds to forcing changes is therefore a critical parameter in determining the response. Recent simulations with the CESM model have found AMOC collapses under climate change scenarios (van Westen, Vanderborght, et al. 2025). The interpretation of this result is that the 'AMOC-off' state is the only statistical equilibrium available under a radiative forcing associated with the RCP8.5 scenario fixed to year 2100. Although such results cannot be confidently extrapolated to other CMIP class models, the result is a warning that the radiative forcing of these RCP scenarios (reached in 2100) could be enough to collapse the AMOC (Drijfhout et al. 2025).

3.3 | Early Warning Signals

The AMOC-MS regime strongly motivates developing early warning signals (EWS) of an AMOC collapse. Direct measurements of the AMOC from arrays and hydrographic data are too short to provide useful EWS. Reconstructions of the AMOC strength from specific sea-surface temperature data in the subpolar gyre have been proposed, indicating that the AMOC strength has decreased by about 15% since the 1950s (Caesar et al. 2018), while surface heat flux-based reconstructions indicate no AMOC weakening between 1963 and 2017 (Terhaar et al. 2025).

Data from such a reconstruction has been used to develop EWS based on "critical slowdown", which one would expect near a saddle-node bifurcation under a linear change in the atmospheric forcing parameter. Analysis shows signatures of a decreasing restoring rate (Boers 2021) with a subsequent estimate of mean tipping time (Ditlevsen and Ditlevsen 2023) of the year 2065 (2037 - 2109, 95% Cl). For a range of datasets and fingerprints, Ben-Yami et al. (2024) find an estimate of 2054–8065 using the same method. Many other EWS have been developed, for example, those based on complex network theory (Feng and Dijkstra 2014) and neural networks (Bury et al. 2021).

The many assumptions on the quality of the data, rate of forcing change and local dynamics (e.g., present-day state is near a saddle-node bifurcation) add to the uncertainty of the EWS usefulness (Ben-Yami et al. 2024). For example, the relation between AMOC and the sea-surface temperature pattern in the subpolar gyre has been criticized, as the latter is influenced by many processes besides the AMOC (Little et al. 2020; He et al. 2022). Optimal statistical EWS are likely based on other observables, such as the salinity at 34° S (Zhu et al. 2023). However, since the time series of observations is relatively short, no signal of an approach to collapse can be detected from these data sets.

The EWS discussed so far (Figure 8) are applicable to tipping as a result of a slow passage through a saddle-node bifurcation. When the classical EWS developed for bifurcation tipping were applied to all CMIP6 historical simulations, no indication for critical slowing down was found (Ben-Yami et al. 2024). For rate-induced transitions, these indicators are not likely to work (Lohmann et al. 2021). Similarly, the development of proper EWS for noise-induced tipping is still in its infancy (Ma et al. 2019), and their predictability is naturally rather limited.

4 | Conclusions, Open Issues and Outlook

4.1 | Conclusions

The IPCC AR6-WG1 report concluded that, based on CMIP6 model results, "the AMOC will very likely decline over the 21st Century for all SSP scenarios. There is medium confidence that the decline will not involve an abrupt collapse before 2100". About 5 years beyond the Weijer et al. (2019) review, there has been substantial progress in that (i) AMOC-MS regimes have been identified in a CMIP5 class model (van Westen et al. 2024), (ii) the relation between the SAF and F_{ovS} has been clarified in more detail (Vanderborght et al. 2025), (iii) the observational data at 34° S in the Atlantic indicate clearly that $F_{ovS} < 0$ (Arumí-Planas et al. 2024). Moreover, the physics of the saddle-node bifurcation L_1 has now been established to be associated with a minimum of F_{ovS} (Vanderborght et al. 2025). According to the analysis of one CMIP5 model, additional feedbacks, besides SAF, have been shown to be small compared to SAF. The analysis of CMIP6 models has shown that biases could be responsible for moving the present-day AMOC state out of this MS regime. Note that even if the AMOC is not currently in a MS regime, it is possible it would enter such a regime and then collapse in future scenarios. Although it will be difficult to prove that the present-day AMOC is in a MS regime, the new results on the issues (i)-(iii) above point in this direction. In summary, there is ample evidence to revisit the IPCC's AMOC stability assessment in the future AR7-WG1 report.

Although array observations (Worthington et al. 2021; Volkov et al. 2024) still show a relatively stable AMOC, early warning indicators (Boers 2021; Ditlevsen and Ditlevsen 2023) show that this has the potential to rapidly change in a few decades. This is because the AMOC clearly exports freshwater out of the Atlantic, that is, the positive SAF and amplification of freshwater perturbations are active. Transient forcing is thus able to shift the AMOC state into a regime where only an "AMOC-off" state exists. This implies that an eventual AMOC collapse is possibly already unavoidable, even under moderate climate change (e.g., SSP2-4.5 scenario (van Westen, Vanderborght, et al. 2025; Romanou et al. 2023)), unless a drastic reduction in greenhouse emissions will occur enabling a safe overshoot (Ritchie et al. 2021). Note that under future forcing an AMOC collapse might lead to a shallow weakly overturning circulation (Baker et al. 2025) but its societal impacts will be just as severe. The recent targeted simulations on AMOC collapses, and the continued AMOC observations, have broadened the evidence base for the AMOC-MS and will hopefully stimulate further systematic research on the AMOC stability.

4.2 | Open Issues

One of the open issues is to quantify the probability that an AMOC collapse will occur before the year 2100. In a noisy

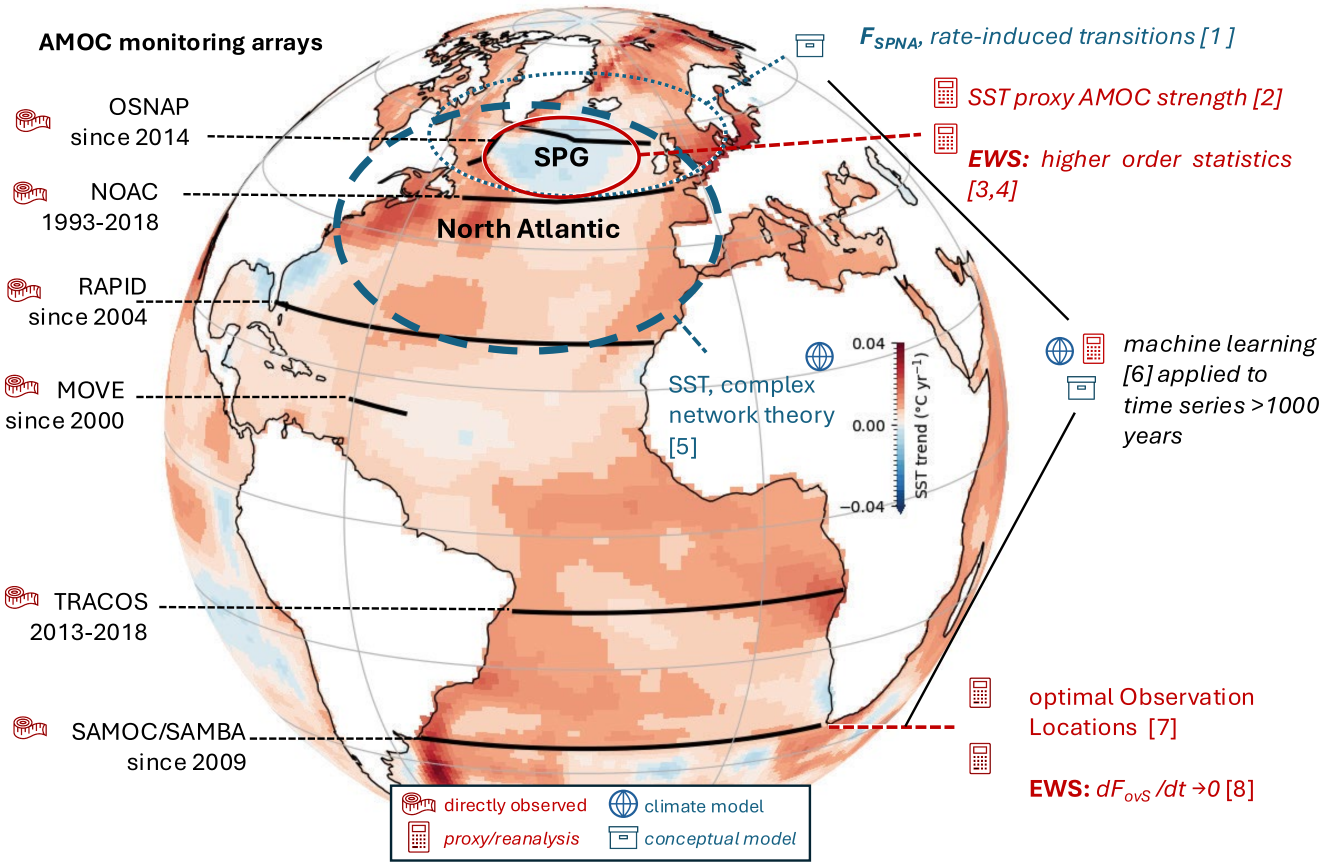

FIGURE 8 | Overview of measurements relevant to the AMOC and early warning indicators. [1] = Ritchie et al. (2023), [2] = Caesar et al. (2018), [3] = Boers (2021), [4] = Ditlevsen and Ditlevsen (2023), [5] = Feng and Dijkstra (2014), [6] = Bury et al. (2021), [7] = Smolders et al. (2025), [8] = van Westen et al. (2024). The background is the observed sea surface temperature trend over the period 1940–2020 from the HadISST dataset (Rayner 2003).

nonlinear climate model, with an AMOC in a MS regime under strong transient forcing, determining these probabilities is a major task. Estimates have been made in box models using rare event techniques (Castellana et al. 2019), two-dimensional models (Baars et al. 2021), and EMICs (Cini et al. 2024), but the application of such techniques to complex models, higher up in the hierarchy, is still challenging. Different models are expected to capture different feedback strengths, which will also affect the transition probability estimates.

A second important open issue is the effect of the behavior of the subpolar gyre (SPG) on the stability of the AMOC. The SPG may also undergo transitions, that is, strong decadal time scale changes in mixed-layer depth and SST, under a transient forcing (Swingedouw et al. 2021) and mechanisms for the existence of a multiple equilibrium regime (Welander 1982; Born and Stocker 2013) have also been proposed. In ocean-only models, such SPG transitions, coupled to AMOC dynamics, lead to a complicated multi-stable regime as recently determined in the VEROS model (Lohmann et al. 2024), which furthermore leads to issues in interpreting EWS from observational data. Even more interesting is the possibility that a shut-down of deep convection, which may occur on faster timescales than an AMOC-shut-down, could tip the AMOC via a tipping cascade (Wunderling et al. 2024), although the connection between changes in convection in the SPG and AMOC changes is far from clear (Lozier et al. 2019).

A third, more fundamental issue (perhaps less relevant to the present day climate change scenario) is whether such an AMOC-MS regime has always existed in the geological past or whether such a regime is connected to specific continental geometry. This is closely related to the issue of why the present-day North Atlantic has a mid-depth overturning (the AMOC), but no such mid-depth circulation occurs in the Pacific. The current view is that the basin selection (either Atlantic or Pacific) for the mid-depth overturning is controlled by the shape of the continents (Ferreira et al. 2018).

4.3 | Outlook: Theory, Modeling and Observations

There is already a start of a theoretical framework to understand the response of the AMOC to climate change both in a low-resolution, diffusive context (Vanderborght et al. 2025) as well as in a weakly diffusive context with parametrized eddies tuned to high-resolution models (Wolfe and Cessi 2011). An extension of this framework to include the effects of resolved ocean eddies, and other climate components, in particular, the atmosphere, ice sheets and sea ice, is needed. The role of the feedbacks, as identified in Vanderborght et al. (2025), is central to changing the density in the Atlantic Ocean with subsequent effects on the AMOC. Additionally, it is important to understand the transient response of the AMOC to climate change during times of changing forcing. Whether the AMOC shuts down for a few centuries into a meta-stable state that is not an equilibrium solution or really shifts to a new equilibrium state is only of academic interest and therefore AMOC-stability analysis should be extended to also address AMOC change, including transient AMOC collapse, from a non-equilibrium point of view.

The strength of the different feedbacks (as described in Section 2 above) will also be forcing dependent, particularly under the transient atmospheric radiative forcing driving future AMOC changes, and hence needs further exploration. For example, global warming may change the sea ice-AMOC feedback strength due to sea-ice loss (Westen et al. 2024) and changes in the ITCZ position (Liu et al. 2024). Also, freshwater export from the North Atlantic subtropical gyre may increase under global warming due to increased surface freshwater loss by evaporation. The varying strength of this feedback is shown to cause the recovery of the AMOC under different radiative forcing scenarios in several model studies (Bonan et al. 2022; Curtis and Fedorov 2024; Garuba et al. 2025).

On the modeling side, the highest priority should be given to reducing biases which are affecting the simulation of the state of the present-day AMOC and its stability. Such biases are not automatically reduced when going to a higher resolution by including ocean eddies (Van Westen and Dijkstra 2024): model developers should focus on improving parameterizations and processes that have been neglected so far (Jackson, Hewitt, et al. 2023). It would also be useful to repeat the feedback analysis as in Vanderborght et al. (2025) to CMIP6 models to see how the biases influence the relative importance of different feedbacks.

Finally, array observations, in particular RAPID, OSNAP and SAMBA, should be given high priority for sustained funding over the next decades as these are the only means to obtain sufficient data for useful EWS and for monitoring the effect of climate change forcing on the AMOC (Frajka-Williams et al. 2023). Together with additional model simulations, using more and more detailed climate models, this should then lead to reliable estimates of the timing and probability of an AMOC collapse.

Author Contributions

Henk A. Dijkstra: conceptualization (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), supervision (equal), visualization (equal), writing – original draft (equal), writing – review and editing (equal). **René M. van Westen:** conceptualization (equal), data curation (equal), formal analysis (equal), resources (equal), software (equal), visualization (equal), writing – original draft (equal), writing – review and editing (equal). **Amber A. Boot:** writing – review and editing (equal). **Jelle Soons:** writing – review and editing (equal). **Emma Smolders:** writing – review and editing (equal). **Jelle Soons:** resources (equal), writing – review and editing (equal). **Elian Vanderborght:** writing – review and editing (equal). **Ayako Abe-Ouchi:** writing – review and editing (equal). **Cristina Arumí-Planas:** writing – review and editing (equal). **Maya Ben-Yami:** writing – review and editing (equal). **Niklas Boers:** writing – review and editing (equal). **Kristin Burmeister:** software (equal), visualization (equal), writing – review and editing (equal). **Paola Cessi:** writing – review and editing (equal). **Peter Ditlevsen:** writing – review and editing (equal). **Sybren Drijfhout:** writing – review and editing (equal). **Matthew H. England:** writing – review and editing (equal). **Caroline Katsman:** writing – review and editing (equal). **Johannes Lohmann:** writing – review and editing (equal). **Jennifer Mecking:** writing – review and editing (equal). **Stefan Rahmstorf:** writing – review and editing (equal). **Meric Srokosz:** writing – review and editing (equal). **Wilbert Weijer:** writing – review and editing (equal). **Richard Wood:** writing – review and editing (equal).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Quantifying the irreducible uncertainty in near-term climate projections.

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Further Reading

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