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Fingerprints of AMOC Decline Are Sensitive to External and Mechanistic Forcing

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Key Points:

- Wind driven ocean circulation can amplify Atlantic meridional overturning circulation (AMOC) decline and cooling in the North Atlantic warming hole
- Labrador Sea salinity gradient must be sufficiently large for the wind driven ocean forcing feedback to activate
- Sea surface temperature based fingerprints of the AMOC are sensitive to mechanistic forcings

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The Atlantic meridional overturning circulation (AMOC) plays a crucial role in past, present, and future climate, and there is substantial interest in using sea surface temperature (SST) as a fingerprint of past AMOC strength. Using a hierarchy of climate model ensembles, we find that the decline in AMOC, and its SST fingerprint within the North Atlantic warming hole region, are sensitive to external forcing level and wind driven ocean forcing. Once external forcing reaches a level at which sea ice melt increases the Labrador Sea vertical salinity gradient, localized cooling and resulting expansion of the sea ice edge decrease vertical mechanical stirring. Under greenhouse gas only forcing, this mechanism plays a large role and under SSP3.70 forcing, it plays a relatively minor role due to larger buoyancy forcing. This implies that an AMOC fingerprint developed from one simulation or external forcing level cannot be applied to other scenarios.

Plain Language Summary

The Atlantic meridional overturning circulation (AMOC) has wide reaching impacts on global climate. Models project that AMOC will weaken into the future, and some studies argue that AMOC has already begun to weaken due to the pattern of surface warming in the North Atlantic. However, it is not yet understood what role, if any, wind stress changes play in a weakening of AMOC or in the surface signature of such a weakening. We compare climate models with and without wind stress changes, under three different external forcing scenarios, to isolate this effect. At high and low forcing levels, wind stress changes do not play a substantial role. At moderate external forcing levels, wind stress changes amplify the AMOC weakening and lead to enhanced cooling in the high latitude North Atlantic.

1. Introduction

The Atlantic meridional overturning circulation (AMOC) plays a crucial role in modern and past climate, by redistributing oceanic heat content, influencing global precipitation and atmospheric circulation (Buckley & Marshall, 2016; Frierson et al., 2013; Marshall & Zanna, 2014; Timmermann et al., 2007; Weijer et al., 2020), and through its role in abrupt climate change such as glacial-interglacial transitions (Lynch-Stieglitz, 2017; Moffa-Sánchez et al., 2019). The AMOC is expected to weaken under anthropogenic climate change (Intergovernmental Panel On Climate Change (IPCC), 2023; Weijer et al., 2020), thus playing an important role in projected future climate (Bellomo et al., 2021; Jackson et al., 2015). A future AMOC decline is expected to be buoyancy forced, as supported by several lines of evidence: (a) Decadal and longer time scale variability in AMOC is primarily buoyancy forced (Buckley et al., 2012, 2015, 2023; Gregory et al., 2005; Larson et al., 2020; Megann et al., 2021; Sévellec et al., 2017), (b) An AMOC decline is simulated by model experiments with a prescribed positive freshwater flux into the high latitude North Atlantic (Jackson et al., 2023; Rahmstorf, 1996; Stouffer et al., 2006; Thomas & Fedorov, 2019), and (c) An AMOC tipping point can be simulated by adding a slowly varying freshwater flux anomaly to the North Atlantic (van Westen et al., 2024).

Direct observations of AMOC strength at 26.5°N from the RAPID array have only been available since 2004 (Johns et al., 2008). Due to the importance of AMOC on climate and the limited availability of direct observations, there is a large focus on reconstructing AMOC variability indirectly over the recent past (Caesar

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et al., 2018) and the last millennium (Caesar et al., 2021; Rahmstorf et al., 2015; Sévellec et al., 2017). These methods of reconstructing AMOC use one or more climate models to obtain a spatial pattern, or "fingerprint," of AMOC variability. One widely used fingerprint is characterized by a relative cooling of sea surface temperatures (SSTs) in the subpolar North Atlantic (Caesar et al., 2018; Chemke et al., 2020; Drijfhout et al., 2012; Sévellec et al., 2017), a feature also referred to as the North Atlantic warming hole (Gervais et al., 2018, 2019, 2020; Hu & Fedorov, 2020; Keil et al., 2020; Menary & Wood, 2018). This fingerprint is based on the fact that models that prescribe freshwater flux into the North Atlantic in order to shut down deep convection show a cooling in the subpolar gyre (Stouffer et al., 2006). This AMOC fingerprint performs well under high forcing levels (such as a doubling of CO_2 or forcing by RCP8.5 until 2100), as judged by the strength of the linear fit between AMOC and relative SST trends in the subpolar North Atlantic (Bellomo et al., 2021; Caesar et al., 2018; Drijfhout et al., 2012; Rahmstorf et al., 2015; Sévellec et al., 2017).

There are a range of processes that can impact SSTs and modify the SST fingerprint. Recent work has highlighted the ability of a model without ocean dynamics to produce a North Atlantic warming hole (He et al., 2022) and demonstrated the importance of atmospheric circulation trends on North Atlantic subpolar gyre SSTs (Li et al., 2022). Others have suggested that aerosol forcing alters the AMOC fingerprint (Little et al., 2020; Zhu et al., 2023), the fingerprint varies over time (Little et al., 2020), and the fingerprint is sensitive to the external forcing level (Mackay et al., 2024; Zhu & Cheng, 2024). A recent paper proposing a positive internal feedback loop between stochastic atmospheric forcing and deep convection relies on wind driven mechanical stirring to complete the loop (Gu et al., 2024). The feedback activates once Arctic sea ice melt drives an increase in the Labrador Sea vertical salinity gradient. Weaker deep convection reduces upward mixing of heat, cooling the Labrador Sea and, later, the entire North Atlantic due to advection by the large scale ocean circulation. This then decelerates sea ice melting, reducing mechanical stirring, and further weakening deep convection. The dependence of this positive feedback loop on wind driven mechanical stirring means that a portion of the AMOC weakening that occurs during a future emissions scenario can be wind driven (McMonigal et al., 2025).

These studies bring into question the link between subpolar North Atlantic SSTs and AMOC. Many processes can alter subpolar North Atlantic SSTs, including turbulent heat fluxes, Ekman heat convergence, the geostrophic circulation, mixed layer depths, and mixed layer entrainment (Buckley et al., 2014; Larson et al., 2020, 2024; Liu et al., 2023; Piecuch et al., 2017) and mean wind stress forcing is necessary to simulate a stable AMOC (Timmermann & Goosse, 2004). An improved understanding of the dynamics driving subpolar North Atlantic SSTs, AMOC trends, and the link between the two is needed to assess whether current or future SST-based AMOC fingerprints could be trustworthy (Terhaar et al., 2025). To address this, we design a model hierarchy to investigate the dependence of a weakening AMOC and its surface fingerprint on mechanical forcing (e.g., buoyancy vs. wind stress forcing) and on external forcing.

2. Materials and Methods

2.1. Ensemble Experiments

We analyze a Community Earth System Model version 2 (CESM2; (Danabasoglu et al., 2020)) model hierarchy under three different forcing levels. The hierarchy includes a fully coupled model ("FCM"), where the ocean and atmosphere are interactive and wind stress changes in the atmosphere can dynamically alter the ocean circulation. The FCM is the setup of CESM2 submitted to the Coupled Model Intercomparison Project version 6 (CMIP6). It consists of atmosphere, ocean, sea ice, land ice (held constant in this study), and land models, which exchange fluxes through the Common Infrastructure for Modeling the Earth (CIME) coupler. Crucially, the ocean and atmosphere exchange fully time varying buoyancy and momentum (via wind stress) fluxes. The FCM ensemble consists of 50 members under historical forcing, 15 members under greenhouse gas only forcing, and 50 members under SSP3.70 forcing (details in Section 2.2). The FCM historical and SSP3.70 ensembles are part of the CESM2 large ensemble (Rodgers et al., 2021) and the greenhouse gas only forcing ensemble is part of the CESM2 single forcing large ensemble (Simpson et al., 2023).

The second hierarchy member, referred to as the mechanically decoupled model ("MDM"), does not allow wind stress changes in the atmosphere to dynamically alter the ocean circulation. The MDM is the same as the FCM, except that the wind stress forcing passed to the ocean from the atmosphere is overwritten by a climatology wind stress calculated from a 50 year pre industrial version of the FCM. Thus, the MDM ocean does not dynamically "feel" wind stress anomalies due to (a) internal variability about the seasonal cycle or (b) changes in external forcing. Turbulent heat fluxes in the MDM use the time varying wind speed simulated by the atmosphere, thus the MDM remains thermodynamically coupled. The MDM ensemble consists of 20 members under historical forcing, 10 members under greenhouse gas only forcing, and 10 members under SSP3.70 forcing. The 10 members under SSP3.70 forcing were branched from a different simulation of five historically forced MDM members. Thus, figures showing the full 1850–2100 time period use five historically forced MDM members to maintain continuity. Note that the time periods shown are a basis for comparison to the real world, but are not expected to replicate observations, due to model biases (Danabasoglu et al., 2020) and internal variability (Deser et al., 2012).

2.2. External Forcing Levels

Both the FCM and MDM are run under the observed variations in all CMIP sources of external forcings, referred to as “historical all forcings” (1850–2014), observed variations in greenhouse gas forcing only, referred to as “historical greenhouse gas forcing only” (1850–2014), and future emissions scenario SSP3.70 (2015–2100) which were branched from five runs of “historical all forcings.” We refer to these forcing levels as historical-all, historical-GHG, and future-SSP370, respectively. Historical-all consists of time varying greenhouse gases, anthropogenic aerosols, smoothed biomass burning aerosols (Fasullo et al., 2022), and volcanic aerosols. Historical-GHG uses the same time varying greenhouse gas forcing as the “all forcings” scenario, but with aerosols and other forcings held constant at 1850 levels (Simpson et al., 2023). Future-SSP370 is a moderate-high future emissions scenario (O’Neill et al., 2016; Riahi et al., 2017).

2.3. Analyses

To isolate the externally forced response from internal variability, we calculate the ensemble mean from each model simulation. One ensemble standard deviation divided by the square root of the number of ensemble members is used to determine significant differences between FCM and MDM (Fu et al., 2024; McMonigal et al., 2023). In such calculations, we allow the ensemble standard deviations to vary in time, as wind driven ocean circulation changes alter internal variability in FCM (S. M. Larson & McMonigal, 2025).

We analyze annual mean anomalies from a 1850–1880 reference state to remove any effect of FCM and MDM mean state differences, and note that such differences are small (Larson et al., 2024; McMonigal et al., 2023). We use the AMOC variable output by CESM2, “meridional overturning circulation” (MOC), which is calculated in depth space, for consistency with prior modeling work (Caesar et al., 2018; Terhaar et al., 2025).

3. Results

3.1. Role of Wind Driven Ocean Circulation Changes on Externally Forced Trends

Under historical-all and future-SSP370 forcings, North Atlantic SST trends remain relatively unaffected by the inclusion of wind driven ocean circulation changes, as evidenced by the similarity between the FCM and MDM under each forcing scenario (Figures 1a, 1b, 1e, and 1f, Figures S2a and S2b in Supporting Information S1). Trends in AMOC are also relatively unaffected by inclusion of wind driven ocean circulation changes, with FCM and MDM showing similar trends in both amplitude and pattern over 1850–2014 (historical-all) and 2015–2100 (future-SSP370) (Figures 1g and 1h, Figure S1 in Supporting Information S1), and both the FCM and MDM show an increase in AMOC strength up until 1980, in response to aerosol forcing (Menary et al., 2020; Robson et al., 2022). This suggests that AMOC trends under these external forcing are buoyancy forced, as anticipated based on prior work such as freshwater hosing experiments (Bellomo & Mehling, 2024; Jackson et al., 2023; Stouffer et al., 2006) and comparison of the pre-industrial FCM and MDM experiments in an earlier version of CESM (Larson et al., 2020).

Under the historical-GHG forcing level, North Atlantic SST trends differ between FCM and MDM. The FCM shows an extensive warming hole, similar although less intense than in the SSP3.70 forcing level, while the MDM shows no discernible warming hole, but rather a limited region of no warming. This implies that changes in the wind driven ocean circulation amplify cooling and can cause a warming hole (Figures 1c and 1d, Figures S2c and S2d in Supporting Information S1). Additionally, under historical-GHG, AMOC weakens significantly more in FCM than in MDM (Figure 1g, Figure S1 in Supporting Information S1 dashed lines).

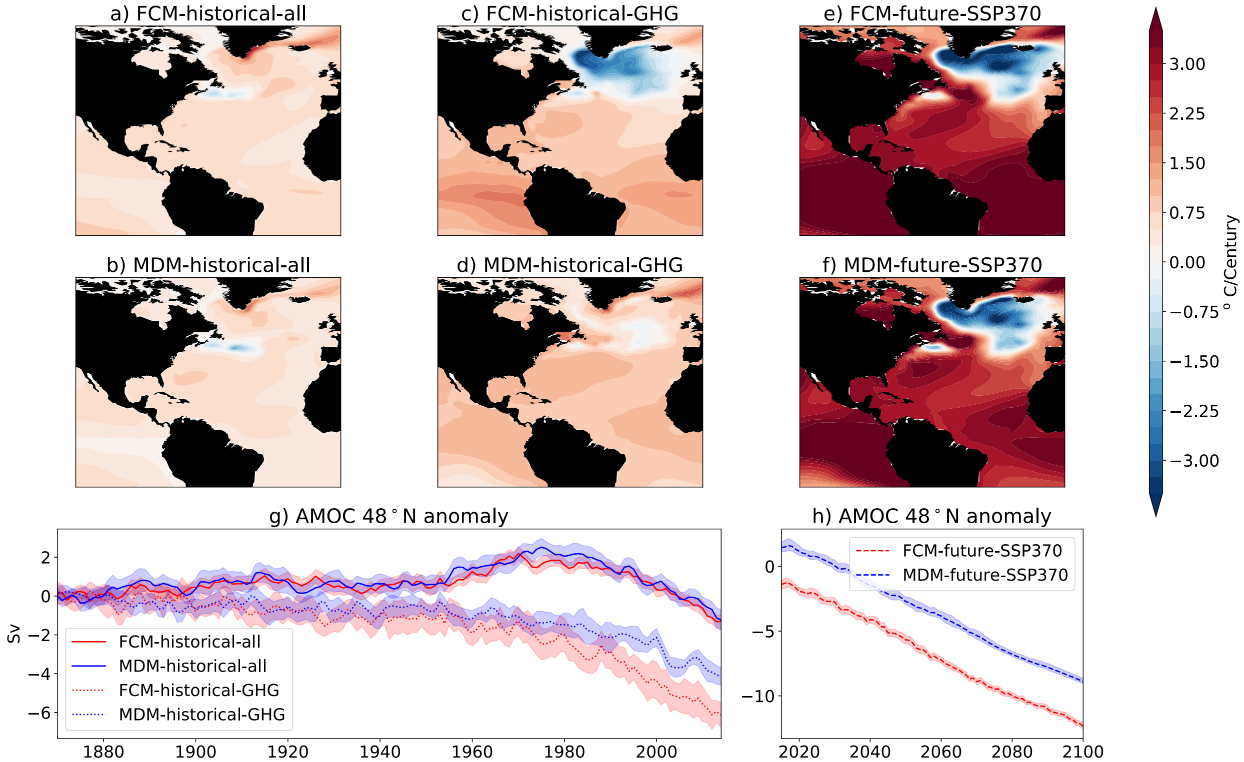

Figure 1. Sea surface temperature (SST) trends in (a) FCM-HIST over 1920–2014, (b) MDM-HIST over 1920–2014, (c) FCM-GHG over 1920–2014, (d) MDM-GHG over 1920–2014, (e) FCM-SSP3-7.0 over 2015–2100, and (f) MDM-SSP3-7.0 over 2015–2100. (g, h) Atlantic meridional overturning circulation across 48°N anomaly in the same experiments.

To investigate the dynamics driving the difference between FCM and MDM AMOC trends under moderate forcing, we regress 5 year low pass filtered ensemble mean sea surface salinity (SSS) in the Labrador Sea onto ensemble mean SST, AMOC, surface heat flux, mixed layer depth, and windstress speed (Figure 2). We use this method because salinity in the Labrador Sea is a crucial component of AMOC weakening. Results are qualitatively similar if we regress AMOC or the first empirical orthogonal function of Labrador SSS onto the same

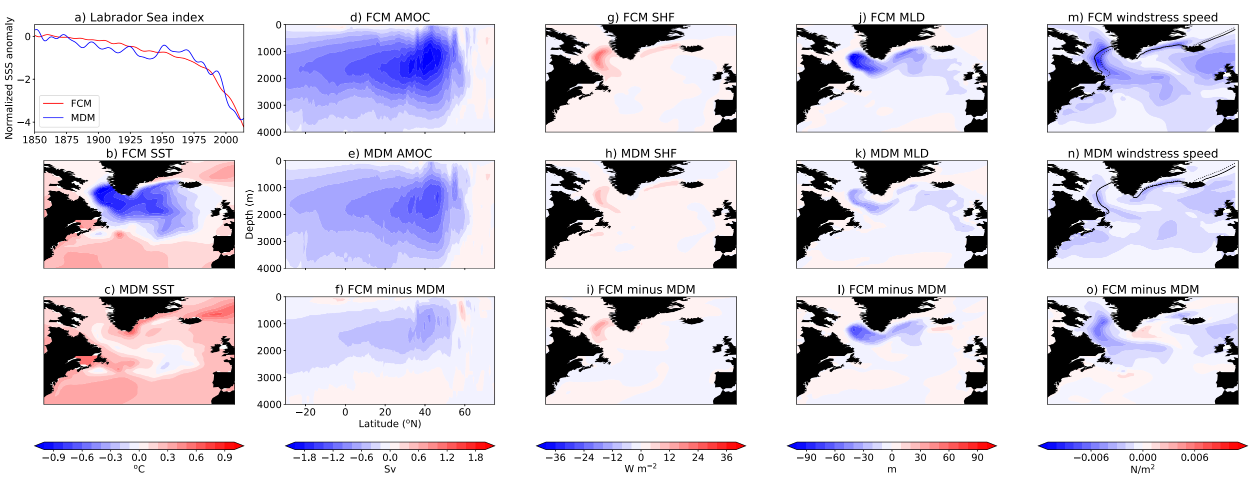

Figure 2. (a) Five year smoothed index of sea surface salinity (SSS) in the Labrador Sea in the greenhouse gas only forced experiments. Regressions of (b) FCM sea surface temperature (SST), (c) MDM SST, (d) FCM Atlantic meridional overturning circulation (AMOC), (e) MDM AMOC, (f) difference of (d) and (e), (g) FCM surface heat flux, (h) MDM surface heat flux, (i) difference of (g) and (h), (j) FCM mixed layer depth, (k) MDM mixed layer depth, (l) difference of (j) and (k), (m) FCM windstress speed, (n) MDM windstress speed, (o) difference of (m) and (n) onto index shown in (a). Solid line on (m) and (n) shows mean 15% sea ice edge over 1850–1879 and dashed line on (m) and (n) shows sea ice edge over 1985–2014.

10.1029/2025GL116307

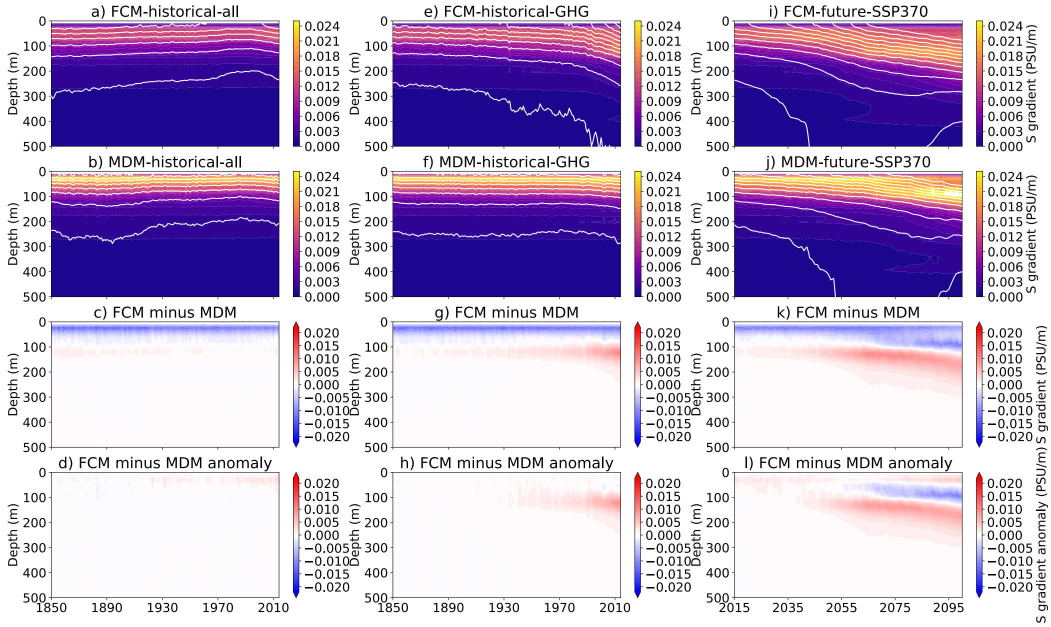

Figure 3. Labrador Sea (51–65°N, 295–315°E) area averaged salinity gradient in (a) FCM-HIST, (b) MDM-HIST, (c) a minus b, (d) anomalies of a minus b, (d) FCM-GHG, (e) MDM-GHG, (f) d minus (e, g) anomalies of d minus (e, h) FCM-3-7.0, (i) MDM-SSP3-7.0, (j) h minus i (k) anomalies of h minus i.

variables. Both FCM and MDM show a decrease in Labrador SSS since 1850 (Figure 2a), broadly matching the observed freshening over recent decades (Tesdal et al., 2018). The decline is smoother over time in FCM than in MDM, likely due to the larger number of ensemble members. Patterns of SST (Figures 2b and 2c) appear similar to the SST trends in Figures 1c and 1d, validating the method. Also consistent with Figure 1, both FCM and MDM show declines in AMOC (Figures 2d and 2e), with a larger decline in FCM (Figure 2f). The larger decline in FCM is evident at mid depths in both hemispheres. Surface heat fluxes, defined as positive into the ocean, show more warming in FCM than MDM (Figures 2g–2i). Thus, surface heat flux trends serve as a dampener to the enhanced SST cooling in FCM compared to MDM. Mixed layer depths shoal in both FCM and MDM, with greater shoaling in FCM (Figures 2j–2l), as expected by the greater AMOC decline. Both FCM and MDM show weakening wind stress speed over the subpolar gyre (Figures 2m and 2n), however, in MDM the change in wind stress is not allowed to dynamically force the ocean. Note that both FCM and MDM show a trend toward an NAO positive state (Figure S3 in Supporting Information S1), suggesting an intensified jet stream.

Given the wind stress trends in FCM and the mechanism proposed by Gu et al. (2024), we would expect that less heat would be mixed vertically upwards in the Labrador Sea in the FCM compared to the MDM. This would lead to a cooling of SSTs regionally through horizontal advection of cold anomalies via the mean large scale ocean circulation. The cooler SSTs facilitate the expansion of the sea ice extent (Figures 2m and 2n, dashed lines). This expanded sea ice extent, as well as changes to the overlying atmospheric circulation which reduce the magnitude of the wind stress (Figure 2o), would reduce mechanical stirring in the Labrador Sea, further reducing the heat mixed up. In the MDM, the change in mechanical stirring due to reduced wind stress cannot operate, short circuiting the feedback. This positive feedback can only activate once the Labrador Sea salinity gradient increases due to Arctic sea ice melt and changes to Arctic runoff (Gervais et al., 2018; Gu et al., 2024; Jahn & Holland, 2013; Nummelin et al., 2016), which begins around 1950 in the historical-GHG run (Figure 3h). Consistent with this timing, the FCM and MDM AMOC strengths and vertical temperature profiles begin to diverge around 1950 (Figure 1g, Figure S4 in Supporting Information S1). The upper 40 m of the MDM Labrador Sea is fresher than the FCM, leading to a mean state difference in the vertical salinity gradient (Figures 3c, 3g, and 3k). However, the proposed mechanism depends on the salinity gradient at the base of the mixed layer, and we do not expect this mean state difference to lead to the AMOC trend differences.

In summary, wind driven ocean circulation changes serve as a positive feedback on the externally forced AMOC weakening under historical-GHG forcing. Why is this mechanism absent in the historical-all, and weak at future-

SSP370 forcing levels? Wind driven positive feedbacks can only amplify the AMOC decline when greenhouse gas driven warming is strong enough to induce a melting of Arctic sea ice melt which increases the Labrador Sea vertical salinity gradient. If this warming level occurs later, as in future-SSP370, the buoyancy forcing is so strong that the contribution of the wind driven positive feedback is smaller (McMonigal et al., 2025). Consistent with this hypothesis, the Labrador Sea vertical salinity gradient never increases in the FCM or MDM historical-all runs (Figures 3a and 3b), presumably because the warming is too small to sufficiently melt Arctic sea ice. Under future-SSP370, the vertical salinity gradient increases around 2040 (Figures 3i, 3k, and 3l), when buoyancy forcing is large enough that it swamps most of the contribution from the wind driven ocean circulation feedback. This mechanism may explain AMOC variability on shorter time scales and in the absence of warming trends, such as decadal to centennial variability (Mehling et al., 2024).

3.2. Role of Wind Driven Ocean Circulation Changes on AMOC Fingerprints

Under historical-GHG forcing, AMOC declines more and SSTs cool more due to a reduction in wind driven mechanical stirring. However, it is not yet clear whether the amount of additional cooling is consistent with the amount of additional AMOC decline, such that an SST-based AMOC fingerprint would still perform reliably.

We construct an AMOC fingerprint by regressing AMOC across 48°N onto SST at each grid point minus global mean SST, in each experiment (Figure S5 in Supporting Information S1). The figure displays SST change for a 1 Sv (10^6 m^3 s^{-1}) decline in AMOC. In all six simulations, AMOC weakening is related to a relative cooling in the North Atlantic subpolar gyre. The FCM and MDM patterns are similar to each other under historical-all and future-SSP370. However, the SST cooling under a given mechanistic forcing (with or without wind stress forcing included) depends on the external forcing. e.g., there is a larger cooling for a 1 Sv AMOC decline in the historical-GHG FCM than in the historical-all FCM. In addition, under historical-GHG, there is a larger cooling in FCM than in MDM, for a 1 Sv decline in AMOC. This implies that the surface signature of an externally forced AMOC decline depends on both external and mechanistic forcing.

To investigate further, we construct a scatter plot of the AMOC fingerprint (defined as SST in the black box on Figure S5 in Supporting Information S1 minus global mean SST) versus AMOC strength, over each year in each scenario (Figure 4). To avoid years with the largest influence from anthropogenic aerosols, we calculate the correlation between the AMOC fingerprint and AMOC over years 1989–2014 in historical-all. In historical-all, both FCM and MDM have moderately high correlations ($R^2 > 0.65$), although with different slopes. In FCM, a 1°C cooling implies a 3.88 Sv AMOC decline, in close agreement with the 3.85 Sv/°C slope found by Caesar et al., 2018 (although Caesar et al., 2018 calculated slope for model spread rather than over time), while in MDM, the same cooling implies only a 2.3 Sv decline. Under historical-GHG, we consider a longer time period of 1920–2014, to match prior studies (Caesar et al., 2018; Ditlevsen & Ditlevsen, 2023). In this external forcing level, FCM has a high correlation ($R^2 = 0.9$) while MDM has a low correlation ($R^2 = 0.26$). Slopes are again different between the two experiments, with the same cooling implying a smaller AMOC decline in FCM than in MDM. Under future-SSP370, both FCM and MDM have very high correlations ($R^2 = 0.98$) with similar slopes implying about 2 Sv of AMOC decline for 1°C cooling. Despite the high correlation, the slope of the line of FCM changes during the 2040–2070 time period when the positive feedback on AMOC weakening and SST cooling is active (black outlined stars in Figure 4c, McMonigal et al., 2025). Results are qualitatively similar if we conduct the same analysis but using subpolar gyre SST (without removing global mean SST; Figure S6 in Supporting Information S1) instead of the AMOC index, or if we use AMOC maximum instead of AMOC across 48°N (Figure S7 in Supporting Information S1).

Our finding that AMOC fingerprints are reliable and only subtly impacted by wind driven ocean circulation changes under future-SSP3.70 agrees with prior work using high emissions scenarios (e.g., Caesar et al., 2018). However, the linear relationship between AMOC and SST is sensitive to the external forcing and, under historical-GHG, sensitive to wind driven ocean circulation changes. Thus, to assume that an AMOC fingerprint derived from a high emissions scenario applies under a different forcing level, such as historical-all, is inappropriate because different dynamics are at play (Section 3.1).

Figure 4d shows 30 year rolling R^2 values between AMOC and the SST based fingerprint in each experiment. The figure combines future-SSP370 with the historical-all scenario it was branched from. With wind driven ocean circulation changes enabled, a high R^2 value emerges around year 2000, after a period of low R^2 values likely linked to aerosol forcing (solid red line in Figure 4d). MDM takes longer to approach the high values (solid blue

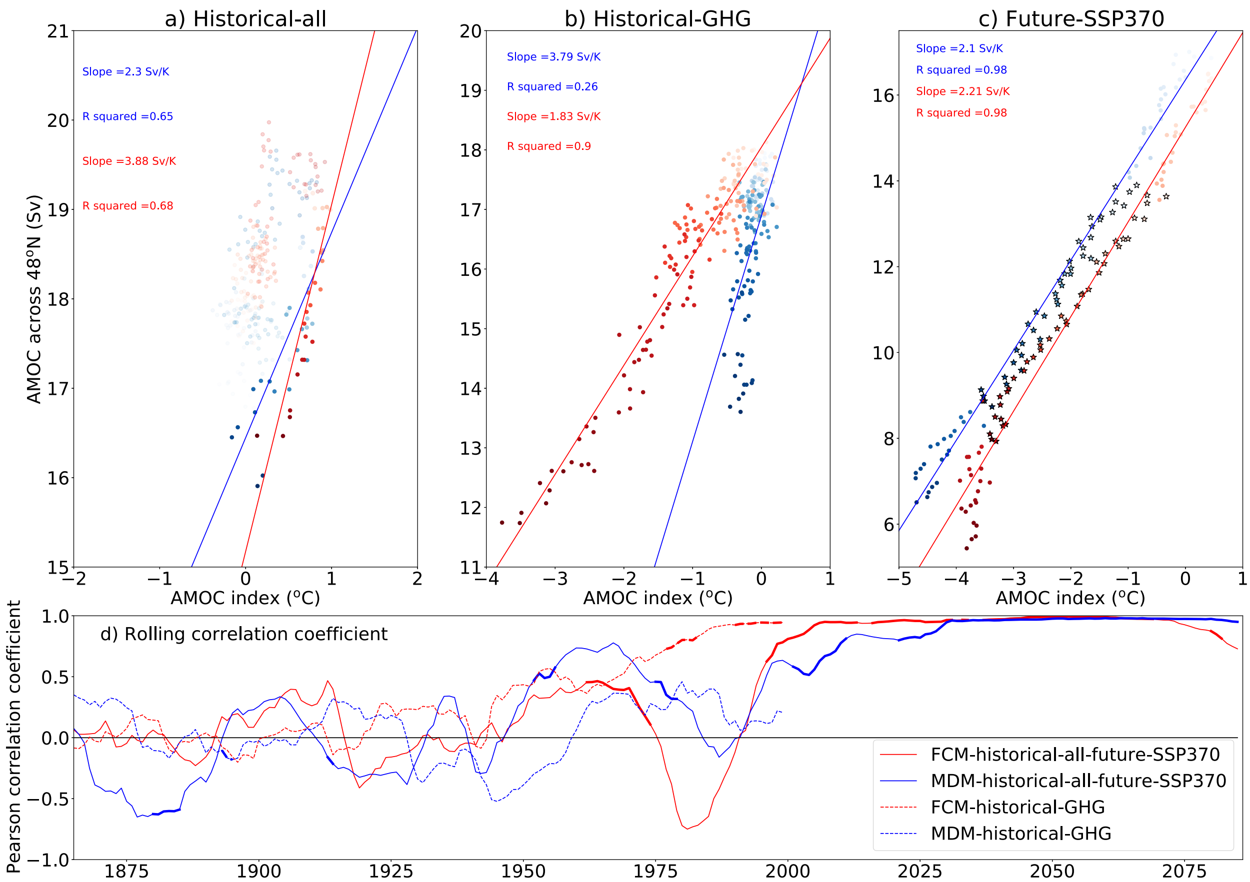

Figure 4. Scatter plot of Atlantic meridional overturning circulation (AMOC) index, defined as mean sea surface temperature (SST) over 46–60°N, 320–345°E minus global mean SST, vs. AMOC across 48°N. Red dots and lines show FCM while blue dots and lines show MDM for (a) HIST, (b) GHG only, and (c) SSP-3.70. In a, only data points from 1989 to 2014 are used to calculate R2 and slope. Data points before 1989 are shown with open symbols. In panel (c), data points from 2040 to 2070 are illustrated as stars with a black outline. (d) Rolling correlation between AMOC across 48°N and AMOC index. Thick lines show statistically significant correlations based on (Ebisuzaki, 1997).

line in Figure 4d). In historical-GHG, the difference between the FCM and MDM R^2 values is more dramatic (dashed lines in Figure 4d), perhaps because buoyancy forcing is relatively weaker at the time when the enhanced Labrador Sea salinity gradient appears in historical-GHG than in future-SSP370.

4. Discussion and Conclusions

Our results imply that the dynamics of the projected AMOC decline are forcing dependent. At external forcing levels that are sufficiently high to weaken the vertical salinity gradient in the Labrador Sea, the AMOC trend is not solely caused by buoyancy forcing, and instead depends on wind driven mechanical forcing. The relative proportion of wind driven versus buoyancy forced AMOC changes is dependent on the external forcing level. In the simulations analyzed here, the AMOC in historical-GHG has the largest contribution of wind driven mechanical forcing, perhaps due to the offsetting effect of anthropogenic aerosols on greenhouse gas driven warming before peak aerosol concentrations were reached in the 1980s (Simpson et al., 2023), leading to a delayed timing of increased Labrador Sea salinity gradient in the historical-all simulation compared to the historical-GHG simulation. Thus, an AMOC fingerprint obtained from one external forcing level need not apply to SSTs from a different external forcing level.

Our analysis uses a single model with a 1° horizontal resolution ocean. Future work should be conducted to determine whether the hypothesized positive feedback loop (Gu et al., 2024; McMonigal et al., 2025) exists within other climate models, higher resolution models, and the real ocean. Additionally, future work could be conducted to more precisely determine which external forcing levels kick off the wind driven ocean circulation feedback loop and the timescale over which it plays a role. This work suggests that the vertical salinity gradient in the Labrador Sea, which is set by sea ice melt, plays a key role in the dynamics of the AMOC decline. Adequately simulating changes to sea ice and stratification in this region is necessary to make projections about a future decline in AMOC.

Data Availability Statement

Data and code to reproduce figures in this manuscript are available at https://zenodo.org/records/15170960 (McMonigal & Larson, 2025a) and https://zenodo.org/records/15231538 (McMonigal & Larson, 2025b) respectively. FCM output is publicly available through the CESM2 Large Ensemble Community Project (https://www.cesm.ucar.edu/community-projects/lens2; Rodgers et al., 2021) and the CESM2 Single Forcing Large Ensemble Project (https://www.cesm.ucar.edu/working-groups/climate/simulations/cesm2-single-forcing-le; Simpson et al., 2023). Code modifications to run the MDM are available through Zenodo at https://doi.org/10.5281/zenodo.6678286 (Larson et al., 2022) and described in Larson et al. (2024).

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