AGU ADVANCING EARTH AND SPACE SCIENCES

Geophysical Research Letters

RESEARCH LETTER

10.1029/2024GL109789

Key Points:

- Sea surface temperature based fingerprint of Atlantic Meridional Overturning Circulation (AMOC) changes under different forcing scenarios
- AMOC in steep decline significantly contributes to North Atlantic warming hole formation, largely due to cloud radiative forcing
- AMOC plays a smaller role in North Atlantic SST variability in historical period and after CO_2 stabilization than during significant warming

Supporting Information:

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

Correspondence to:

Q. Mackay and L. Li,
mackayq@oregonstate.edu;
lfl5240@psu.edu

Citation:

Mackay, Q., Fan, Y., Karnauskas, K. B., & Li, L. (2024). Nonstationarity of the Atlantic meridional overturning circulation's fingerprint on sea surface temperature. *Geophysical Research Letters*, *51*, e2024GL109789. https://doi.org/10.1029/2024GL109789

Received 19 APR 2024
Accepted 12 SEP 2024

Author Contributions:

Data curation: Quinn Mackay, Yifei Fan
Formal analysis: Quinn Mackay, Yifei Fan
Funding acquisition: Kristopher B. Karnauskas
Investigation: Quinn Mackay, Yifei Fan
Methodology: Quinn Mackay, Yifei Fan
Software: Quinn Mackay, Yifei Fan
Validation: Quinn Mackay, Yifei Fan
Visualization: Quinn Mackay, Yifei Fan
Writing – original draft: Quinn Mackay

Nonstationarity of the Atlantic Meridional Overturning Circulation's Fingerprint on Sea Surface Temperature

Quinn Mackay[1], Yifei Fan[2], Kristopher B. Karnauskas[3,4], and Laifang Li[2,5,6]

[1]College of Earth, Ocean, and Atmospheric Science, Oregon State University, Corvallis, OR, USA, [2]Department of Meteorology and Atmospheric Science, Penn State University, University Park, PA, USA, [3]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO, USA, [4]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA, [5]Institute of Computational and Data Sciences, Penn State University, University Park, PA, USA, [6]Environmental and Earth Science Institute, Penn State University, University Park, PA, USA

Abstract Sea surface temperature (SST) has been increasing since industrialization with rising greenhouse gases. However, a warming hole exists in the North Atlantic where SST has cooled by 0.4 K/century during 1900–2017. It has been argued that this cooling is due to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC), and subpolar North Atlantic SST has thus been utilized to estimate AMOC variability. We assess the robustness of subpolar North Atlantic SST as a proxy for AMOC strength under historical forcing, abrupt quadrupling of CO_2, and a medium future emissions pathway, finding that AMOC's fingerprint on SST depends upon forcing scenarios. AMOC is important in warming hole development during significant warming periods, although SST may introduce uncertainties for AMOC reconstruction in stabilized regimes due to diverse forcing mechanisms and decadal variability. Our results caution against using SST alone as a proxy for AMOC variability—both on paleoclimatic and contemporary time scales.

Plain Language Summary As greenhouse gas concentrations increase, the global average sea surface temperature (SST) has risen in response at a rate of 1.4 K/Century since industrialization; however, there exists an area in the North Atlantic decreasing in SST, the North Atlantic Warming Hole (NAWH). Some have argued that the cooling is due to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC), a global circulation current that transports warm equatorial surface water northward. We analyze forcing scenarios using a global climate model under three differing forcing mechanisms, one similar to the real world, one where CO_2 initially starts at four times pre-industrial levels and then held constant, and one based on a medium level future emissions scenario. From this, we study the quality of North Atlantic SST as a proxy for AMOC strength. Our study finds that the impact of the AMOC on SST changes between scenarios, and thus we believe that North Atlantic SST may introduce uncertainty into paleoclimatic studies attempting to reconstruct AMOC change. Additionally, we found that a slowdown of the AMOC plays an important role in the cooling of the North Atlantic when AMOC is slowing rapidly (or "shutting down"), although has a more minimal impact in less extreme scenarios.

1. Introduction

Globally, Earth has seen a dramatic sea surface temperature (SST) increase over the past century in response to a radiative imbalance from anthropogenic greenhouse gas emissions, rising at a rate of 1.4 K/century (Huang et al., 2017). However, in the subpolar North Atlantic, an absence of warming exists dubbed the North Atlantic Warming Hole (NAWH; Hansen et al., 2010). The SST averaged over the NAWH region has cooled at a rate of 0.4 K/century within the period of 1870–2016 (Keil et al., 2020). Shifting ocean circulation due to climate change can modify SSTs (Winton et al., 2013), and some studies have attributed the NAWH to a slowdown of the Atlantic Meridional Overturning Circulation (AMOC; Rahmstorf et al., 2015; Chemke et al., 2020). The AMOC is a large-scale ocean circulation responsible for northward heat transport from the equatorial regions, thus leaving a SST imprint over the subpolar North Atlantic (Rahmstorf et al., 2015; Zhang, 2008). This SST fingerprint has been utilized as a proxy of AMOC intensity, and the observed NAWH has been suggested as an evidence of AMOC weakening in the past decades (Caesar et al., 2018). North Atlantic SST has also been historically used as a proxy for paleoceanographic and historical studies of AMOC variability (Caesar et al., 2021).

Writing – review & editing: Quinn Mackay, Yifei Fan, Kristopher B. Karnauskas

A slowdown of the AMOC could have wide-reaching climate effects and drastically impact Northern European climate (Lozier, 2010) with a full shutdown causing a surface air temperature anomaly of up to −8 K in certain northern reaches of Europe and northeast North America, which would have profound implications on regional ecosystems and agriculture (Jackson et al., 2015). Understanding the current state of the AMOC is important, and in warmer climates it is under consensus of global climate models that the AMOC will slow down; however, due to a lack of direct observation, twentieth-century AMOC change remains inconclusive (Kilbourne et al., 2022; Weijer et al., 2020). The ability to detect AMOC changes from SST-based proxies has been debated (Jackson & Wood, 2020; Keil et al., 2020; Li et al., 2021, 2022; Little et al., 2020), as subpolar North Atlantic SST variability on decadal and longer timescales could be driven by multiple mechanisms, such as air-sea interaction, intrinsic atmospheric variability, external forcing, and gyre circulations, without an explicit role of AMOC-induced oceanic heat transport (Alexander-Turner et al., 2018; Bellomo et al., 2018; Booth et al., 2012; Clement et al., 2015; Fan et al., 2023; Hu & Fedorov, 2020; Li et al., 2022; Mann et al., 2021; O'Reilly et al., 2019). Additionally, North Atlantic SST positive feedback mechanisms have been documented, which could sustain a preexisting warming hole (Gervais et al., 2018; Karnauskas et al., 2021).

In this study, we revisit the subpolar North Atlantic SST as a proxy of AMOC strength using a global climate model that reasonably simulates the NAWH. We analyze SST and AMOC changes in an experiment in which CO_2 is abruptly quadrupled from pre-industrial levels and simulations under a medium future emissions pathway and historical forcing scenario. Previous studies have shown that subpolar North Atlantic SST patterns differ between models that exhibit a large versus small AMOC decline models (Bellomo et al., 2021). This study expands on this finding by quantifying the subpolar North Atlantic SST-AMOC relation to determine SST's reliability as a AMOC proxy amongst different forcing scenarios. We also perform surface heat budget analysis to quantify different physical processes' contribution to subpolar North Atlantic SST changes under different forcing scenarios.

2. Data and Methods

2.1. The MPI-ESM1-2 Model

The output from the high-resolution version of the Max Planck Institute Earth System Model (MPI-ESM1.2-HR; Müller et al., 2018) is used in this study. The MPI-ESM1.2-HR model was specifically chosen as it simulates an observed past cooling trend in the subpolar North Atlantic, in both magnitude and spatial pattern (Fan et al., 2024), as shown in Figure S1 in Supporting Information S1 (see details in the in Supporting Information S1).

Three model scenarios are considered: the abrupt 4×CO_2, historical, and the Shared Socioeconomic Pathway 2–4.5 (SSP245) simulations. The historical simulation has 10 ensemble members with varying initial conditions. The SSP245, a medium emissions pathway with an increase of 4.5 W/m^2 between 1750 and 2100, has two ensemble members. We perform all analysis on the ensemble mean for the historical and SSP245 experiments to reduce potential impact of internal climate variability. Between the scenarios, we analyze the period of 1850–2099 as a basis for comparison.

The defined NAWH region has a latitude range of 48.5°–61°N and a longitude range of 38°W through 15°W, marked by dotted lines on Figure 1a. The AMOC is defined as the zonally and vertically integrated northward volume transport, thus a function of latitude and depth with a unit of $m^3\ s^{-1}$, or more universally, Sverdrup (1 Sv $\equiv 10^6\ m^3\ s^{-1}$). Previous studies have typically represented the strength of the two-dimensional AMOC for SST-based analysis studies through an AMOC index (Caesar et al., 2018; Rahmstorf et al., 2015). In this case, we defined the AMOC index as the maximum streamfunction below 500 m, between the latitudes of 10S and 90N. Various specific latitudes tested for the AMOC index did not change the key conclusions of this study. The model output variable, overturning mass stream function, corresponds to its common definition if multiplied by the seawater density (e.g., 1e9 kg s^{-1} = 1 Sv, assuming 1000 kg m^{-3} saltwater density).

While this study focuses on the AMOC in depth coordinates, prior work has shown that the AMOC in density coordinates is a more relevant quantity for understanding the circulation in the subpolar North Atlantic and the attendant transports of heat and freshwater (Buckley et al., 2023; Lozier et al., 2019; Lozier, 2023; Zhang & Thomas, 2021). We chose to implement depth-based coordinates due to the previous assumption of the NAWH index being an AMOC proxy is based on a definition in depth-coordinates (Caesar et al., 2018; Rahmstorf et al., 2015). Therefore, we believe our analysis will provide additional insight by maintaining consistency with

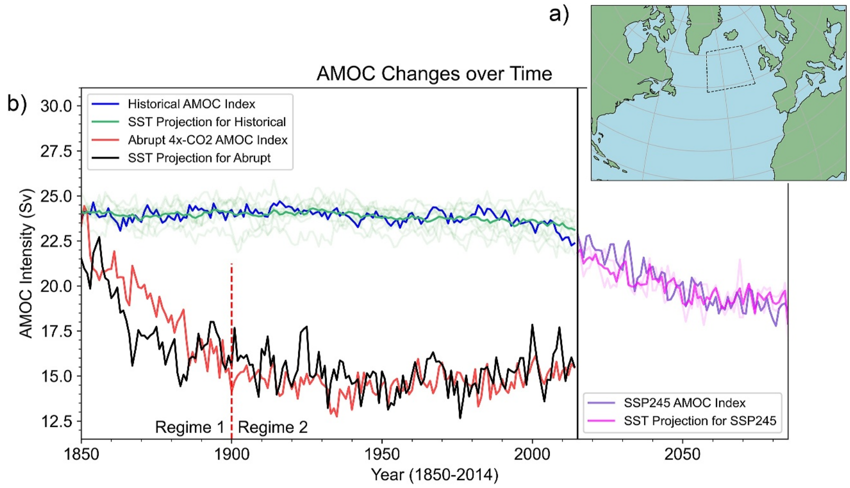

Figure 1. (a) A map demarking the location of the North Atlantic Warming Hole (NAWH). (b) Time series of AMOC intensity in Historical, Abrupt 4xCO_2 and SSP245 scenarios. The Abrupt scenario is split into two distinct regimes, one characterized by a quick and constant decline, and the other by a stabilized "shutdown". The historical simulation is averaged along 10 realizations, while SSP245 is averaged over 2. The WH-index and AMOC-index were regressed to project AMOC based on the WH-index.

previous AMOC fingerprint studies (Jackson & Wood, 2020; Little et al., 2020; Zhang, 2008). Model analysis studies have also shown that MPI-ESM1.2-HR simulates an AMOC consistent with observations (Gutjahr et al., 2019).

2.2. Regime Separation Within Data Set

We separate the analysis into four major regimes according to AMOC intensity and rate of AMOC changes. The first regime is the historical simulation, dominated by variability among realizations. The abrupt 4xCO_2 scenario is divided into two separate regimes. Regime 1 is dominated by a continuous decline of the AMOC from ∼24 to ∼14 Sv (41%) over 50 years, allowing us to analyze the transient relationship between the AMOC slowdown and the NAWH. Regime 2 holds a stable but variable AMOC between 13 and 16 SV after climate stabilization. SSP245 exhibits its own regime over an 85-year period with an AMOC decline from ∼23 to ∼18 Sv, allowing for analysis of moderate AMOC slowdown (Fig. 1b).

2.3. Partial Temperature Change (PTC) Analysis

We calculated the partial temperature changes (PTCs) for warming hole SST from each of six major forcing mechanisms: (a) surface shortwave radiation from surface albedo feedback (SAF), (b) cloud radiative forcing (CRF), (c) the non-SAF induced clear-sky shortwave radiation, (d) downward clear-sky longwave radiation, (e) ocean heat storage and (f) surface sensible and latent heat fluxes. Terms (e) and (f) are summed into a seventh term, as they are two physically associated processes, where SST is mostly controlled by oceanic processes, and changes in surface heat flux respond to reduce ocean-induced signals. Combining these terms helps give a better overview of the physical processes responsible for local SST change, as they largely negate each other. As a whole, these PTCs equal the total SST change for the region. Calculating the PTCs within a region allows individual analysis of the processes contributing to SST changes and is a useful tool for understanding the causes of the NAWH. They are calculated identically as in Fan et al. (2021, 2024), utilizing the already proven successful method outlined in those papers, and a full description of the analysis method for calculation of each of the PTCs is outlined in Supplemental Information S1.

3. Results

3.1. Relationships Between AMOC and Subpolar North Atlantic SST

Regression analysis of the model scenarios show different AMOC-WH relationships (Figure 2). Three different SST measurements are used; (a) NAWH SST, which is the averaged annual-mean SST across the entire warming

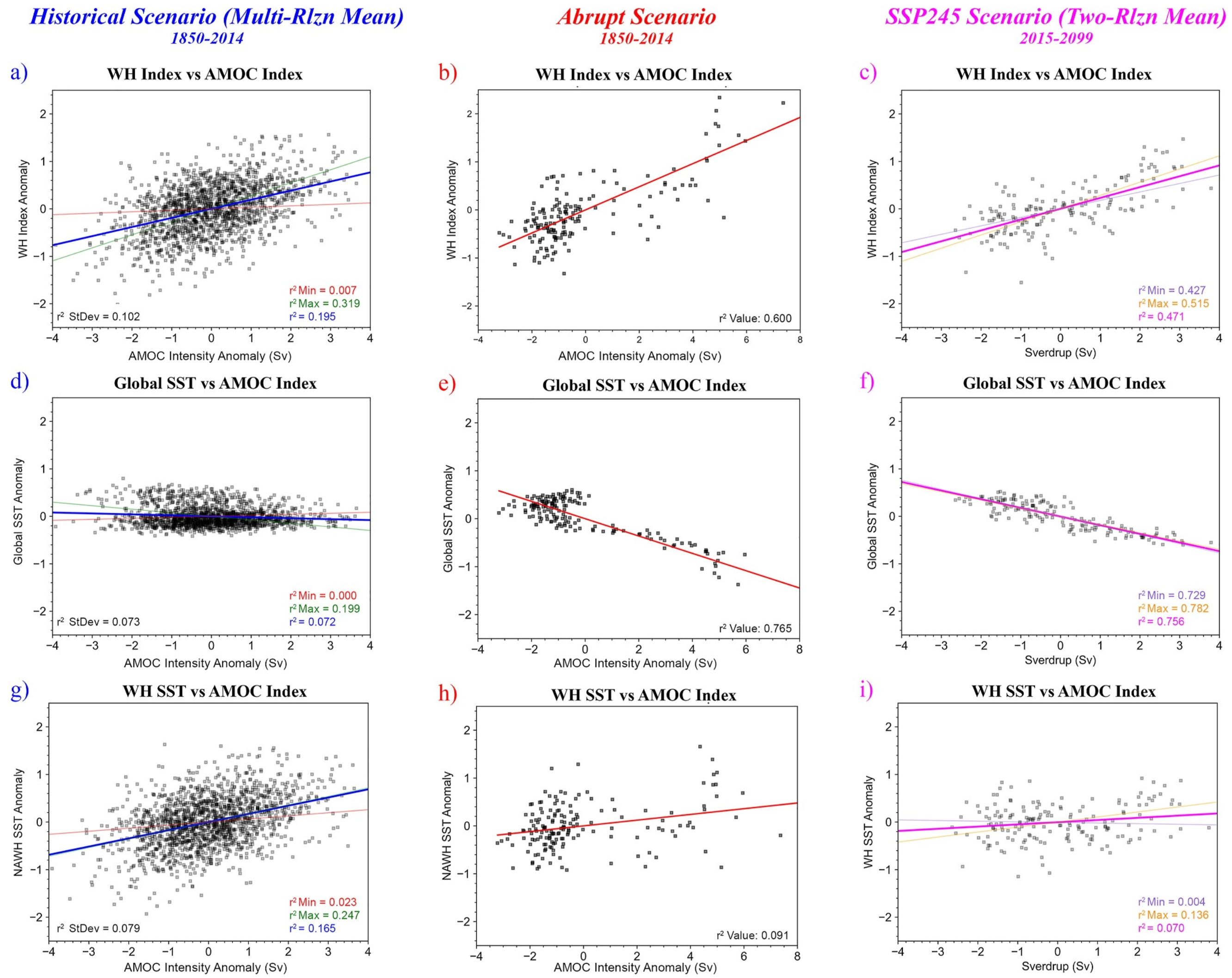

Figure 2. Correlation between AMOC intensity anomaly, and NAWH-index anomaly (WH SST—GLOBAL SST) (a–c), global SST anomaly (d–f) or NAWH SST anomaly (g–i). The leftmost column is the historical scenario, the middle column is the abrupt scenario, and SSP245 is the rightmost column. Historical and SSP245 are calculated from multiple realizations (2 for SSP245; 10 for Historical). All p-values are statistically significant ($p < 0.05$).

hole, (b) Global SST, averaged globally, and (c) NAWH index, defined as the NAWH minus Global SST difference. The NAWH-index is separate from purely NAWH SST, as it demonstrates the difference between the NAWH SST change and the global-mean SST change. Overall, there is a stronger linear correlation in the abrupt 4×CO_2 ($r^2 = 0.600$) and SSP245 ($r^2 = 0.471$) scenarios between the NAWH-index and AMOC intensity than in the historical simulation ($r^2 = 0.195$; Figures 2a–2c). This implies an especially strong relationship between AMOC and the NAWH-index in scenarios with significant AMOC slowdown. Breaking down the NAWH-index, the correlation comes mainly from the relationship of global mean SST and AMOC (Figures 2e and 2f, Abrupt: $r^2 = 0.765$, SSP245: $r^2 = 0.756$), since correlation between local SST and AMOC is minimal (Figures 2h and 2i, Abrupt: $r^2 = 0.091$; SSP245: $r^2 = 0.070$). The opposite is seen in the historical period, where correlation seen in the NAWH-index is almost entirely due to changing local SST (Figure 2g; $r^2 = 0.165$), rather than the global mean SST (Figure 2d; $r^2 = 0.072$). All stated correlations have a p-value <0.05. Thus, significant AMOC related cooling and simulataneous GHG warming as seen in the Abrupt and SSP245 scenarios are the cause of the correlation between the NAWH-index and the AMOC, rather than any ability of local SST in the NAWH region to serve as a proxy for the AMOC (Little et al., 2020). We also state that this regression analysis suggests the uncertainties in the processes driving SST in the WH region under different forcing scenarios, but does not cast doubt on the existence of cooling in the NAWH region.

To examine the robustness of SST as a proxy for AMOC strength, we use the NAWH-index relationship derived from each scenario to project the AMOC (Figure 1b). The NAWH-index is used as it is the most common measurement for AMOC SST proxies, with similar indexes used in Caesar et al. (2018) and Rahmstorf et al. (2015). We also calculated the root mean square error (RMSE) for each scenario, an effective method of determining error between predicted and simulated values, where a higher RMSE value indicates decreased accuracy between the projections and observations. Each of the scenarios has a varying number of ensemble members, and thus we only analyzed the first ensemble member presented to avoid scenarios with higher variability from limited ensemble members exhibiting an unnaturally high RSME. Additionally, the RMSE was normalized by dividing by the mean streamfunction of each scenario, to allow for comparison between each forcing scenario (multiplied by 100 for clarity; raw values in Table S1 in Supporting Information S1). The historical scenario has a normalized RMSE of 4.53, SSP245 of 5.64, and the abrupt scenario of 9.45, although Regime 1 has a higer RMSE of 11.12 compared to Regime 2's 7.88. The higher RMSE of the abrupt scenario indicates more inaccurate projections, but is opposite to the patterns suggested within Figure 2, which indicate that more abrupt scenarios more closely correlate with AMOC patterns. This pattern is potentially explained by the magnitude of difference between projected and observed values during a rapid change being higher than in more stable periods, even though the overall correlation is stronger for abrupt scenarios. Additionally, according to Figure 1b and the statistical analysis, while the overall AMOC trend roughly follows the NAWH index, significant variability remains in all scenarios with high levels of decadal uncertainties in the projected AMOC intensity when compared to the observed values. This complements recent studies suggesting that factors other than the AMOC, both internal and externally driven, can influence the NAWH (Bellomo et al., 2018; Booth et al., 2012; He et al., 2022; Li et al., 2022; Mann et al., 2021). Thus, subpolar North Atlantic SST—the NAWH index in particular—is not a reliable proxy to reconstruct and infer AMOC changes under different forcing scenarios due to external forcing mechanisms and high variability.

3.2. AMOC's Changing Fingerprint in Response to Forcing Scenarios

The simulated spatial patterns of SST also change between scenarios, with a weak NAWH emerging in the historical scenario (Figure 3a), strong in Abrupt Regime 1 (Figure 3b), no pattern in Regime 2 (Figure 3c), and moderate in SSP245 (Figure 3d). Leveraging the variability within each scenario, regardless of the emergence of a NAWH, the pattern of the statistical relationship between AMOC and subpolar North Atlantic SST is not particularly robust in terms of regression patterns and explained variance (Figures 3e–3l). Analysis of the AMOC fingerprint in the four distinct forcing scenarios shows dramatic differences in the AMOC fingerprint (Figures 3e–3h).

In the historical simulation, the fingerprint of a negative AMOC anomaly is cooling in the entire North Atlantic basin (Figure 3e), a pattern not shared by the actual SST change in the same simulation (Figure 3a). This implies that the AMOC slowdown is likely not the primary reason why the NAWH occurs in the simulated location under the historical scenario. In contrast, Regime 1 of 4×CO_2 and SSP245 show patterns of cooling in the WH region and warming in regions of the Gulf Stream per −1 Sv that match the actual SST change (Figures 3b–3d and 3f, 3h). Consequently, it is likely that AMOC slowdown is moderately responsible for the North Atlantic SST patterns during periods of rapid warming, consistent with previous studies linking AMOC slowdown to the development of the NAWH in high GHG forcing scenarios (e.g., Drijfhout et al., 2012; Liu et al., 2020; Sgubin et al., 2017). Areas of moderate correlation ($r^2 > 0.30$) also exist within the Abrupt Regime 1 and SSP245 scenarios, in the areas with the most significant cooling trends. Finally, post-slowdown AMOC plays a minimal role in the SST change in Regime 2, as the pattern indicated in Figure 2g for ΔK/+1 Sv is disparate from the actual SST pattern shown in Figure 2c. This is further demonstrated for both historical and Regime 2, as the AMOC has a modest relationship with SST in the subpolar North Atlantic ($r^2 < 0.20$ in Figures 3i and 3k), although the existence of some statistically significant correlation in the regions may indicate that AMOC plays a minor role in the SST patterns.

These results imply that the subpolar North Atlantic SST shows more relationship with the AMOC slowdown in moderate to rapid warming scenarios. However, the usage of the NAWH index as a proxy for AMOC during equilibrated climate regimes or where only subtle changes are occurring may introduce significant uncertainties, as AMOC change plays only a minor role in shaping the subpolar SST patterns in these climate states. The results encourage the use of multiple proxies when analyzing AMOC changes, especially in paleoclimatic studies focusing on periods not characterized by rapid, transient change.

10.1029/2024GL109789

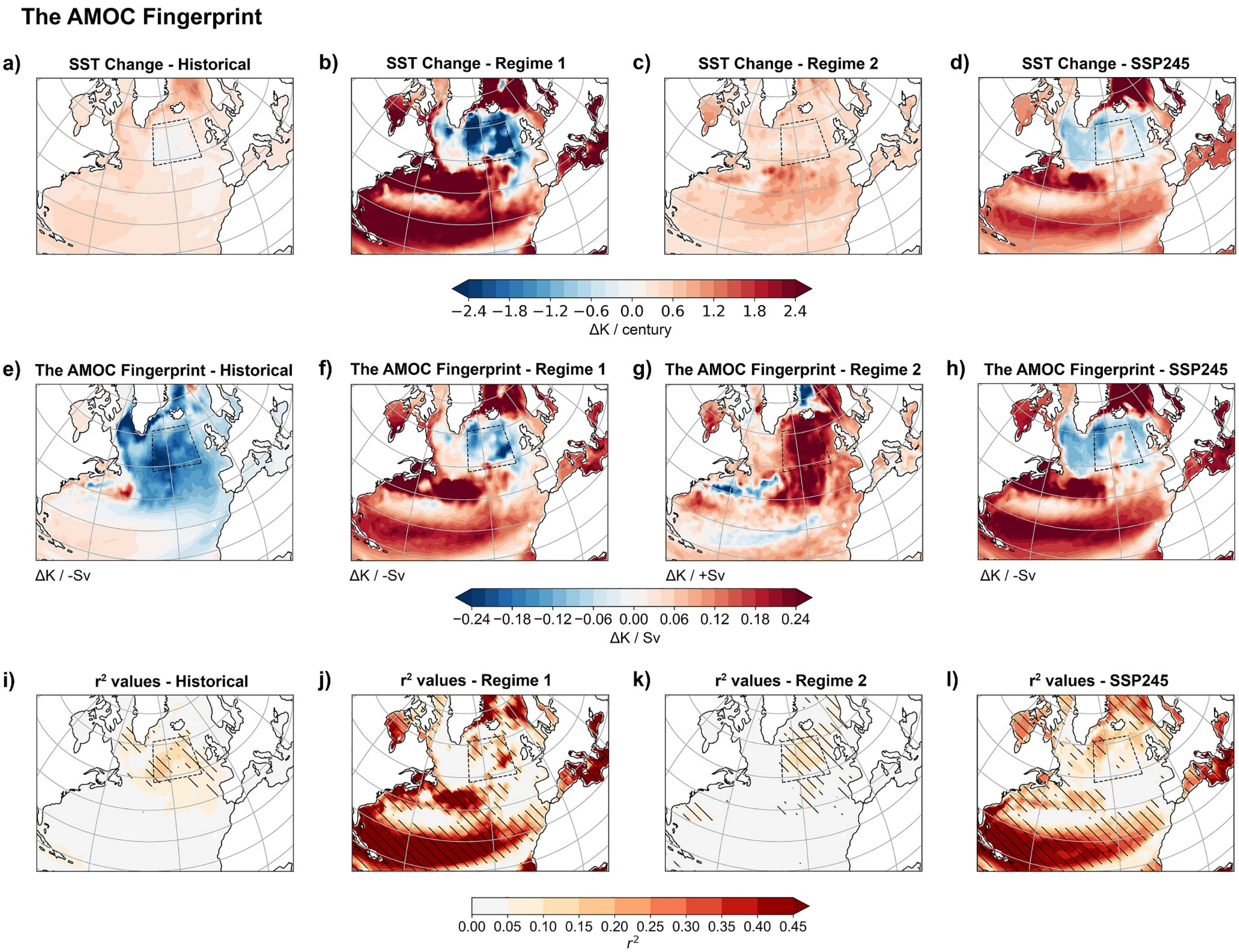

Figure 3. The SST trend (unit: K/century) over the subpolar North Atlantic as derived from the (a) Historical Simulation; (b) the decline period (Regime 1) of Abrupt 4xCO_2; (c) the stabilized period (Regime 2) of Abrupt 4xCO_2; and (d) the moderate pathway SSP245. (e–h) are the SST-based AMOC fingerprints calculated as a regression between AMOC-index and SST, with a lag of 0 years, showing the potential SST change per 1 Sv change in AMOC. Sub-figure (g) is shown in ΔK/+Sv, as the overall SST pattern is warming in the NAWH during the scenario. (i–l) are the r^2 values, with hatches to signify a $p < 0.05$. The dashed boxes outline the spatial extent of the subpolar North Atlantic warming hole in the MPI-ESM1.2-HR model.

3.3. Partial Temperature Change Analysis of Shifting Fingerprint

The tenuous relationship between AMOC and subpolar North Atlantic SST motivates a quantitative analysis of the underlying causes of subpolar North Atlantic SST variability. To analyze the causes of the NAWH SST change under different forcing scenarios, we conduct a partial temperature change (PTC) analysis (see details in Supporting Information S1) on the NAWH in the four regimes (Figure 4). PTCs are regressed onto the AMOC-index (Figure 4a; K/−1 Sv) to help understand the specific mechanisms behind SST change as AMOC varies. Additionally, contributions from different PTC terms across the four scenarios indicate that the underlying causes of the North Atlantic SST change is non-stationary (Figure 4b; K/century).

Both the PTCs and AMOC's fingerprints on them vary in each of the forcing scenarios, indicating that different processes are responsible for North Atlantic SST change under different scenarios. The cooling in abrupt Regime 1 and SSP245 is predominantly driven by CRF (Figure 4b), which is associated with a strong cloud albedo response to GHG forcing. Although the ocean heat transport leads to substantial cooling in the NAWH region, the induced cooling is largely offset by warming effect of surface sensible and latent heat fluxes, which could be due to a surface turbulent flux feedback (Figures 4b and Hausmann et al., 2017). As a result, the thermal imbalance between heat storage and sensible and latent heat flux (T5 + T6) plays a smaller role than CRF does in driving the

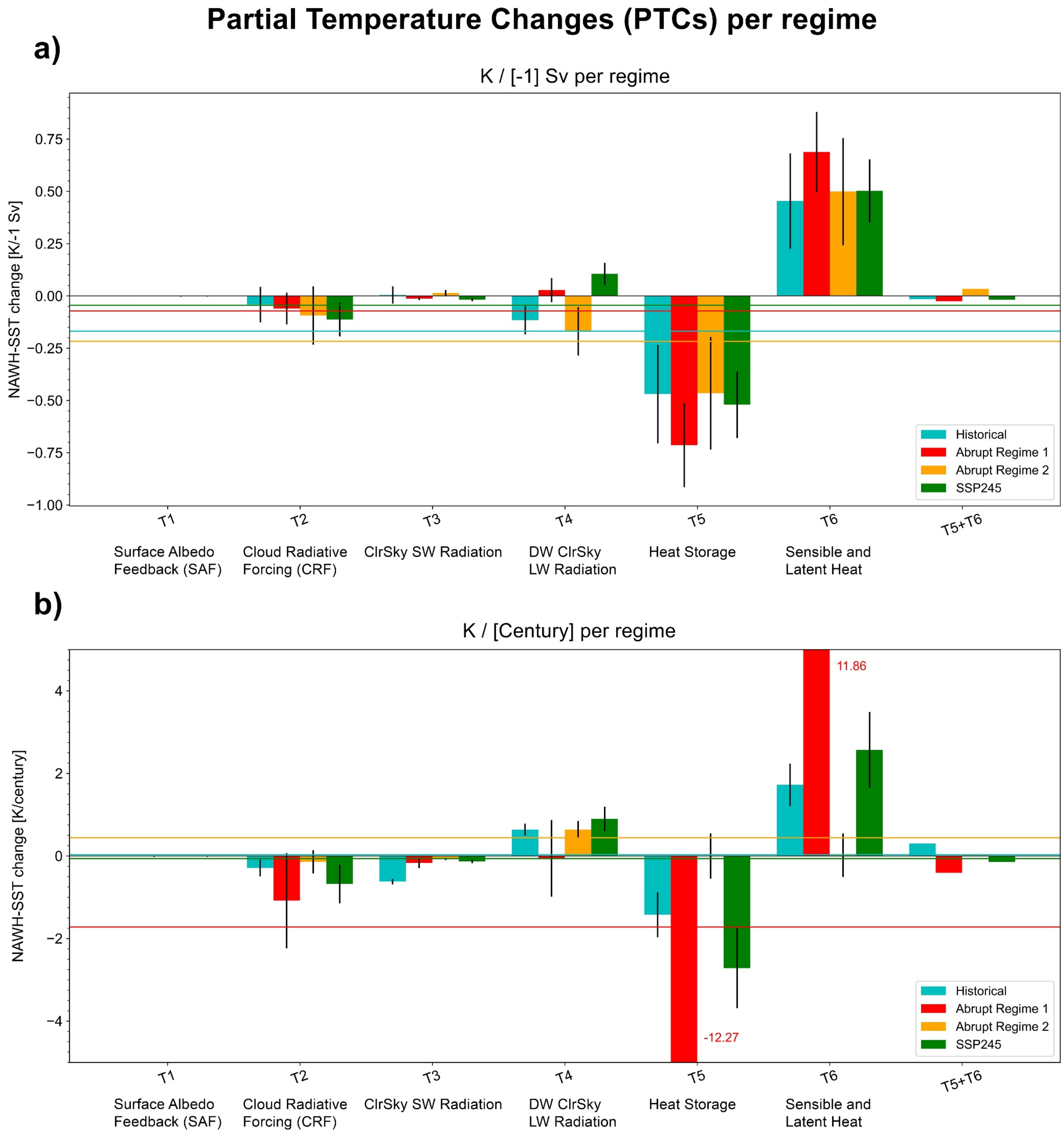

Figure 4. Partial Temperature Changes (PTC) terms that contribute to SST in (a) degrees K per −1 Sv, calculated by regression, and (b) total degrees K per century. There exists six different processes: Surface Albedo Feedback, Cloud Radiative Forcing, Clear-sky Shortwave Radiation, Downward Clear-sky Longwave Radiation, Heat Storage, and Sensible and Latent Heat. Horizontal lines are the measurement sums, which are equivalent to SST trend simulated by the MPI-ESM-1-2-HR model. Error bars indicate 90% confidence interval.

cooling. Despite the extreme CO_2 forcing, little change is seen in surface downward clear-sky longwave radiation, probably because the radiative effect of lower atmosphere temperature change compensates the warming expected from increased GHG concentration. Overall, the predominant cooling mechanisms over time for abrupt Regime 1 and SSP245 are consistent with AMOC weakening mechanisms, as they both display similar PTC traits.

10.1029/2024GL109789

This supports that AMOC intensity changes have an impact on the NAWH in a transient regime, especially due to CRF's influence.

In contrast, in Regime 2, we see no temperature change effects over time from either heat storage and surface turbulent heat fluxes or CRF (Figure 4b). The modest warming (0.44 K/century) in this regime (Figure 3c) is solely due to an increase in surface downward clearsky longwave radiation. This differs from the AMOC forced PTCs (yellow bars in Figure 4a), suggesting that the AMOC plays little role in driving the low-frequency variability of subpolar North Atlantic SST during this period. Meanwhile, the historical simulation sees little SST change over time (0.03 K/century; Figure 3a; blue line in Figure 4b), because the cooling effects from CRF and clear sky shortwave radiation balance the warming effects from clearsky longwave radiation and a positive thermal imbalance between heat storage and surface turbulent heat fluxes. Among these, the cooling mechanisms by heat storage and CRF are consistent with the effect of AMOC weakening, while others are not. Therefore, the absence of warming might be partially associated with the mild AMOC decline (−0.63 Sv/century) in the historical period.

4. Summary and Conclusions

In this study, we analyzed historical and transient simulations of a high-resolution climate model to understand the stationarity of the relationship between the AMOC and the NAWH. A decline of AMOC plays a notable role in NAWH development under rapid warming, however, detecting AMOC changes from local SST is not possible in less dramatic regimes. The AMOC fingerprint shifts between forcing scenarios, with atmospheric radiative processes playing a significant role in driving subpolar North Atlantic SST variability, introducing some uncertainty to SST-based AMOC proxies. Our heat budget analysis suggests complexity of the subpolar North Atlantic SST change, prompting further studies to better understand drivers of regional SST changes. Overall, the importance of SST change caused by atmospheric processes, such as CRF and clear-sky longwave radiation, introduces uncertainties into SST measurements as a proxy for AMOC variability.

This study comes to a similar conclusion as Little et al. (2020), building on the results with a different model structure and mechanistic investigation. Thus, we hence call for caution when subpolar North Atlantic SST-based proxies are applied to infer AMOC change in paleoclimatic studies. Our finding has also recently been supported by Zhu et al. (2023) and Zhu and Cheng (2024), which note that the strong interdecadal variability and low North Atlantic fingerprint sensitivity introduces too much noise to properly extrapolate AMOC's impacts. To clarify, our study does not nullify the statement about the AMOC decline in recent decades or the near future and its impact on North Atlantic climate, but rather aims at addressing the uncertainties associated with SST-based reconstruction of the AMOC, which are widely used but all subject to the same potential biases illustrated here.

One caveat to note is that the conclusions in this study are based on one single model. Although this model reasonably simulates the observed NAWH in the historical period, the results presented here may be model dependent and subject to limitations. Thus, studies using different models will be needed to help determine the robustness of this study. Nonetheless, the varying relationships between the AMOC and the NAWH suggest future studies could focus on further analysis of other drivers or indicators of the subpolar North Atlantic SST change, such as gyre circulation, radiative forcing (Bellomo et al., 2018; Booth et al., 2012; Mann et al., 2021) and atmospheric dynamics (He et al., 2022; Li et al., 2022) and on exploring other metrics, such as salinity (Zhu et al., 2023) to detect AMOC change. Studies investigating AMOC fingerprints in density rather than depth coordinates may prove insightful. Approaches that can objectively integrate disparate proxies and lines of evidence such as machine learning may also prove useful in the future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The MPI-ESM1-2-HR model output is publicly accessible via CMIP6 (Coupled Model Intercomparison Project Phase six) at https://pcmdi.llnl.gov/CMIP6/. This study has uploaded all data sets needed to reproduce the shown figures to Zenodo, available at Mackay et al., 2024.

ERSST Version 5 and Kaplan SST data was used in this supporting information (Huang et al., 2017; Kaplan et al., 1998). It was provided by the NOAA PSL, Boulder, Colorado, USA, from their website at https://psl.noaa.gov/.

HADISST data was used in this supporting information (Rayner et al., 2003). It was provided by the Met Office Hadley Centre, Exeter, UK, from their website at: https://www.metoffice.gov.uk/hadobs/hadisst/.

Acknowledgments

- Quinn Mackay thanks NSF for providing funds for the research via grant AGS-1852428.
- Laifang Li and Yifei Fan are supported by the seed grant provided by the ICDS at the Pennsylvania State University.
- Kristopher B. Karnauskas is supported by the NASA Sea Level Change Science Program, Award #80NSSC20K1123.

References

Alexander-Turner, R., Robson, J., & Ortega, P. (2018). How robust are the surface temperature fingerprints of the Atlantic overturning meridional circulation on monthly time scales? *Geophysical Research Letters*, *45*(8), 3559–3567. https://doi.org/10.1029/2017gl076759

Bellomo, K., Angeloni, M., Corti, S., & von Hardenberg, J. (2021). Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. *Nature Communications*, *12*(1), 3659. https://doi.org/10.1038/s41467-021-24015-w

Bellomo, K., Murphy, L. N., Cane, M. A., Clement, A. C., & Polvani, L. M. (2018). Historical forcings as main drivers of the Atlantic multidecadal variability in the CESM large ensemble. *Climate Dynamics*, *50*(9–10), 3687–3698. https://doi.org/10.1007/s00382-017-3834-3

Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T., & Bellouin, N. (2012). Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, *484*(7393), 228–232. https://doi.org/10.1038/nature10946

Buckley, M. W., Susan Lozier, M., Desbruyères, D., & Evans, D. G. (2023). Buoyancy forcing and the subpolar Atlantic meridional overturning circulation. *Philosophical Transactions of the Royal Society A*, *381*(2262). https://doi.org/10.1098/rsta.2022.0181

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2021). Current Atlantic meridional overturning circulation weakest in last millennium. *Nature Geoscience*, *14*(3), 118–120. https://doi.org/10.1038/s41561-021-00699-z

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*(7700), 191–196. https://doi.org/10.1038/s41586-018-0006-5

Chemke, R., Zanna, L., & Polvani, L. M. (2020). Identifying a human signal in the North Atlantic warming hole. *Nature Communications*, *11*(1), 1540. https://doi.org/10.1038/s41467-020-15285-x

Clement, A., Bellomo, K., Murphy, L. N., Cane, M. A., Mauritsen, T., Rädel, G., & Stevens, B. (2015). The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science*, *350*(6258), 320–324. https://doi.org/10.1126/science.aab3980

Drijfhout, S., van Oldenborgh, G. J., & Cimatoribus, A. (2012). Is a decline of AMOC causing the warming hole above the North Atlantic in observed and modeled warming patterns? *Journal of Climate*, *25*(24), 8373–8379. https://doi.org/10.1175/JCLI-D-12-00490.1

Fan, Y., Chan, D., Zhang, P., & Li, L. (2024). Disagreement on the North Atlantic cold blob formation mechanisms among climate models. *Journal of Climate*, *37*(16), 4061–4078. https://doi.org/10.1175/jcli-d-23-0654.1

Fan, Y., Liu, W., Zhang, P., Chen, R., & Li, L. (2023). North Atlantic Oscillation contributes to the subpolar North Atlantic cooling in the past century. *Climate Dynamics*, *61*(11–12), 5199–5215. https://doi.org/10.1007/s00382-023-06847-y

Fan, Y., Lu, J., & Li, L. (2021). Mechanism of the centennial subpolar North Atlantic cooling trend in the FGOALS-g2 historical simulation. *Journal of Geophysical Research: Oceans*, *126*(9). https://doi.org/10.1029/2021JC017511

Gervais, M., Shaman, J., & Kushnir, Y. (2018). Mechanisms governing the development of the North Atlantic warming hole in the CESM-LE future climate simulations. *Journal of Climate*, *31*(15), 5927–5946. https://doi.org/10.1175/jcli-d-17-0635.1

Gutjahr, O., Putrasahan, D., Lohmann, K., Jungclaus, J. H., von Storch, J. S., Brüggemann, N., et al. (2019). Max Planck Institute Earth System model (MPI-ESM1.2) for the high-resolution model Intercomparison project (HighResMIP). *Geoscientific Model Development*, *12*(7), 3241–3281. https://doi.org/10.5194/gmd-12-3241-2019

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*, *48*(4), RG4004. https://doi.org/10.1029/2010RG000345

Hausmann, U., Czaja, A., & Marshall, J. (2017). Mechanisms controlling the SST air-sea heat flux feedback and its dependence on spatial scale. *Climate Dynamics*, *48*(3–4), 1297–1307. https://doi.org/10.1007/s00382-016-3142-3

He, C., Clement, A. C., Cane, M. A., Murphy, L. N., Klavans, J. M., & Fenske, T. (2022). A North Atlantic warming hole without ocean circulation. *Geophysical Research Letters*, *49*(19). https://doi.org/10.1029/2022gl100420

Hu, S., & Fedorov, A. V. (2020). Indian Ocean warming as a driver of the North Atlantic warming hole. *Nature Communications*, *11*(1), 4785. https://doi.org/10.1038/s41467-020-18522-5

Huang, B., Thorne, P., Banzon, V., Boyer, T., Chepurin, G., Lawrimore, J., et al. (2017). NOAA extended reconstructed Sea Surface temperature (ERSST), version 5. [Dataset]. *NOAA National Centers for Environmental Information*. https://doi.org/10.7289/V5T72FNM. Accessed 21 June 2023.

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. v., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*, *45*(11–12), 3299–3316. https://doi.org/10.1007/s00382-015-2540-2

Jackson, L. C., & Wood, R. A. (2020). Fingerprints for early detection of changes in the AMOC. *Journal of Climate*, *33*(16), 7027–7044. https://doi.org/10.1175/JCLI-D-20-0034.1

Karnauskas, K. B., Zhang, L., & Amaya, D. J. (2021). The atmospheric response to North Atlantic SST trends, 1870–2019. *Geophysical Research Letters*, *48*(2). https://doi.org/10.1029/2020gl090677

Kaplan, A., Cane, M. A., Kushnir, Y., Clement, A. C., Blumenthal, M. B., & Rajagopalan, B. (1998). Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research: Oceans*, *103*(C9), 18567–18589. https://doi.org/10.1029/97jc01736

Keil, P., Mauritsen, T., Jungclaus, J., Hedemann, C., Olonscheck, D., & Ghosh, R. (2020). Multiple drivers of the North Atlantic warming hole. *Nature Climate Change*, *10*(7), 667–671. https://doi.org/10.1038/s41558-020-0819-8

Kilbourne, K. H., Wanamaker, A. D., Moffa-Sanchez, P., Reynolds, D. J., Amrhein, D. E., Butler, P. G., et al. (2022). Atlantic circulation change still uncertain. *Nature Geoscience*, *15*(3), 165–167. https://doi.org/10.1038/s41561-022-00896-4

Li, F., Lozier, M. S., Bacon, S., Bower, A. S., Cunningham, S. A., de Jong, M. F., et al. (2021). Subpolar North Atlantic western boundary density anomalies and the meridional overturning circulation. *Nature Communications*, *12*(1), 3002. https://doi.org/10.1038/s41467-021-23350-2

Li, L., Susan Lozier, M., & Li, F. (2022). Century-long cooling trend in subpolar North Atlantic forced by atmosphere: An alternative explanation. *Climate Dynamics*, *58*(9–10), 2249–2267. https://doi.org/10.1007/s00382-021-06003-4

Little, C. M., Zhao, M., & Buckley, M. W. (2020). Do surface temperature indices reflect centennial-timescale trends in Atlantic meridional overturning circulation strength? *Geophysical Research Letters*, *47*(22). https://doi.org/10.1029/2020GL090888

Liu, W., Fedorov, A. V., Xie, S.-P., & Hu, S. (2020). Climate impacts of a weakened Atlantic meridional overturning circulation in a warming climate. *Science Advances*, *6*(26), eaaz4876. https://doi.org/10.1126/sciadv.aaz4876
Lozier, M. S. (2010). Deconstructing the conveyor belt. *Science*, *328*(5985), 1507–1511. https://doi.org/10.1126/science.1189250
Lozier, M. S. (2023). Overturning in the subpolar North Atlantic: A review. *Philosophical Transactions of the Royal Society A*, *381*(2262). https://doi.org/10.1098/rsta.2022.0191
Lozier, M. S., Li, F., Bacon, S., Bahr, F., Bower, A. S., Cunningham, S. A., et al. (2019). A sea change in our view of overturning in the subpolar North Atlantic. *Science*, *363*(6426), 516–521. https://doi.org/10.1126/science.aau6592
Mackay, Q., Fan, Y., Karnauskas, K., & Li, L. (2024). Nonstationarity of the Atlantic Meridional Overturning Circulation's fingerprint on sea surface temperature. [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.13294890
Mann, M. E., Steinman, B. A., Brouillette, D. J., & Miller, S. K. (2021). Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science*, *371*(6533), 1014–1019. https://doi.org/10.1126/science.abc5810
Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., et al. (2018). A higher-resolution version of the Max Planck Institute Earth System model (MPI-ESM1.2-HR). *Journal of Advances in Modeling Earth Systems*, *10*(7), 1383–1413. https://doi.org/10.1029/2017ms001217
O'Reilly, C. H., Zanna, L., & Woollings, T. (2019). Assessing external and internal sources of Atlantic multidecadal variability using models, proxy data, and early instrumental indices. *Journal of Climate*, *32*(22), 7727–7745. https://doi.org/10.1175/JCLI-D-19-0177.1
Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., & Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, *5*(5), 475–480. https://doi.org/10.1038/nclimate2554
Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. v., Rowell, D. P., et al. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(14). https://doi.org/10.1029/2002jd002670
Sgubin, G., Swingedouw, D., Drijfhout, S., Mary, Y., & Bennabi, A. (2017). Abrupt cooling over the North Atlantic in modern climate models. *Nature Communications*, *8*(1), 14375. https://doi.org/10.1038/ncomms14375
Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 models predict significant 21st century decline of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, *47*(12). https://doi.org/10.1029/2019GL086075
Winton, M., Griffies, S. M., Samuels, B. L., Sarmiento, J. L., & Frölicher, T. L. (2013). Connecting changing ocean circulation with changing climate. *Journal of Climate*, *26*(7), 2268–2278. https://doi.org/10.1175/jcli-d-12-00296.1
Zhang, R. (2008). Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, *35*(20), L20705. https://doi.org/10.1029/2008GL035463
Zhang, R., & Thomas, M. (2021). Horizontal circulation across density surfaces contributes substantially to the long-term mean northern Atlantic Meridional Overturning Circulation. *Communications Earth & Environment*, *2*(1), 112. https://doi.org/10.1038/s43247-021-00182-y
Zhu, C., & Cheng, L. (2024). Sensitivity of AMOC fingerprints under future anthropogenic warming. *Geophysical Research Letters*, *51*(3). https://doi.org/10.1029/2023gl107170
Zhu, C., Liu, Z., Zhang, S., & Wu, L. (2023). Likely accelerated weakening of Atlantic overturning circulation emerges in optimal salinity fingerprint. *Nature Communications*, *14*(1), 1245. https://doi.org/10.1038/s41467-023-36288-4