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Key Points:
- Most models underestimate the amplitude of low-frequency AMOC variability
- Given stronger low-frequency AMOC variability, linkages between the AMOC and the AMV and associated impacts on northern hemisphere surface temperature are stronger
- Atlantic decadal predictability is much higher (lower) in models with stronger (weaker) low-frequency AMOC variability

Supporting Information:
- Supporting Information S1

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Underestimated AMOC Variability and Implications for AMV and Predictability in CMIP Models

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Abstract The Atlantic Meridional Overturning Circulation (AMOC) has profound impacts on various climate phenomena. Using both observations and simulations from the Coupled Model Intercomparison Project Phase 3 and 5, here we show that most models underestimate the amplitude of low-frequency AMOC variability. We further show that stronger low-frequency AMOC variability leads to stronger linkages between the AMOC and key variables associated with the Atlantic multidecadal variability (AMV), and between the subpolar AMV signal and northern hemisphere surface air temperature. Low-frequency extratropical northern hemisphere surface air temperature variability might increase with the amplitude of low-frequency AMOC variability. Atlantic decadal predictability is much higher in models with stronger low-frequency AMOC variability and much lower in models with weaker or without AMOC variability. Our results suggest that simulating realistic low-frequency AMOC variability is very important, both for simulating realistic linkages between AMOC and AMV-related variables and for achieving substantially higher Atlantic decadal predictability.

Plain Language Summary Our results provide a new perspective for understanding the important role of the Atlantic Meridional Overturning Circulation in Atlantic multidecadal variability and associated impacts and predictability. Our results indicate that the linkages between the Atlantic Meridional Overturning Circulation and Atlantic multidecadal variability, as well as the associated climate impacts and Atlantic decadal predictability, could be substantially hampered in Coupled Model Intercomparison Project models due to their underestimation of the amplitude of low-frequency Atlantic Meridional Overturning Circulation variability.

1. Introduction

Estimating the amplitude of low-frequency Atlantic Meridional Overturning Circulation (AMOC) variability in observations is very important given its potentially profound climate impacts. Currently, the longest available direct observation of AMOC is from the RAPID program since 2004 (Smeed et al., 2014, 2016, 2018). Due to the very short observational records, a direct estimate of the amplitude of low-frequency AMOC variability is not yet available. In this study, for the first time, we infer the amplitude of low frequency AMOC variability indirectly using both the RAPID AMOC observations and the much longer record of an observed AMOC fingerprint derived from a subsurface ocean temperature data set for the period 1955–2015 (Joyce & Zhang, 2010; Yan et al., 2017; Zhang, 2008, 2017; Zhang & Zhang, 2015). A comparison between model simulations and these inferred observations suggests that most Coupled Model Intercomparison Project Phase 5 (CMIP5) models underestimate the amplitude of low-frequency AMOC variability.

The AMV, a large-scale mode of multidecadal variability in the Atlantic Ocean (Kerr, 2000), has many important regional and global-scale climate impacts (Enfield et al., 2001; Goldenberg et al., 2001; Klotzbach & Gray, 2008; Klotzbach et al., 2015; Knight et al., 2006; Semenov et al., 2010; Sutton & Hodson, 2005; Zhang & Delworth, 2006; Zhang et al., 2007). The Atlantic multidecadal variability (AMV) is associated with coherent multidecadal variations of sea surface temperature (SST), sea surface salinity (SSS), upper ocean heat content (UOHC), upper ocean salt content (UOSC), and net downward surface heat flux (F_{SFC}) in the subpolar North Atlantic (Zhang, 2017), a region that can be directly influenced by the AMOC and associated heat/salt advection (McCarthy et al., 2015; Robson et al., 2016; Zhang, 2017; Zhang & Zhang, 2015). Previous studies show that the simulated correlations between the AMOC and the AMV SST signal in fully coupled models are not robust and vary substantially between models (Ba et al., 2014; Keenlyside et al., 2016; Zhang & Wang, 2013), challenging our understanding of the role of AMOC in the AMV and its associated climate impacts

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in the real world. A natural question is whether the diverse linkages between the AMOC and the AMV SST signal in different models are related to the simulated amplitudes of low-frequency AMOC variability. This study aims to answer this question by analyzing both CMIP3 and CMIP5 models.

Previous studies (Semenov et al., 2010; Zhang et al., 2007) also show that the AMV can influence multidecadal variations of northern hemisphere mean surface temperature. Therefore, it is reasonable to hypothesize that the degree to which the AMV affects hemispheric-scale climate might be related to the amplitude of low-frequency AMOC variability. Indeed, we find that models with stronger low-frequency AMOC variability have a much stronger linkage between the subpolar AMV SST fluctuations and northern hemisphere surface air temperature variability.

Decadal predictions have significant social, economic, and environmental implications. However, it is unknown how the Atlantic decadal predictability will change with the amplitude of the low-frequency AMOC variability. In this study, we also investigate this problem using CMIP3 and CMIP5 fully coupled models, as well as CMIP3 slab ocean models (i.e., models with the atmospheric component coupled to a slab ocean) with no AMOC variability.

2. Data and Methods

The directly observed AMOC Index at 26°N for the 12-year period 2004–2015 is obtained from the RAPID-WATCH MOC monitoring project (Smeed et al., 2014, 2016, 2018). The AMOC fingerprint is often defined as the leading empirical orthogonal function/principal component of detrended annual mean subsurface ocean temperature anomalies at 400 m or 0 to 700-m UOHC in the extratropical North Atlantic (80°W–0°E, 20°N–65°N) in previous studies (Joyce & Zhang, 2010; Yan et al., 2017; Zhang, 2008, 2017; Zhang & Zhang, 2015). The AMOC anomalies at northern high latitudes lead the AMOC fingerprint by several years due to a slow southward propagation of AMOC anomalies (Zhang, 2010; Zhang et al., 2011; Zhang & Zhang, 2015). To enhance data reliability, in this study we use 0 to 700-m UOHC for the observed AMOC fingerprint, which is derived from an objectively analyzed data set of annual-mean ocean temperature anomalies for the period 1955–2015 (Levitus et al., 2012). The UOHC gives a very similar AMOC fingerprint to that based on 400-m temperature (Figure S1 in the supporting information). The historical AMOC Index at 26°N is reconstructed from the observed AMOC fingerprint (leading principal component) and calibrated with the observed RAPID AMOC Index at 26°N (Figure S2a and supporting information). The estimates of the standard deviation of the 12-year AMOC trends and the amplitude of the low frequency AMOC variability for observations (Figure 1) are then inferred from the time series of the reconstructed AMOC Index at 26°N. We also develop a justification of the AMOC reconstruction method using fully coupled models, which is independent from the simulated amplitudes of low-frequency AMOC variability in models. The model justification suggests that the uncertainty of the calibration is likely small and the AMOC reconstruction is reasonable but may underestimate the true amplitude of low-frequency AMOC variability (supporting information). The AMOC Index is defined as the maximum zonally integrated Atlantic meridional overturning stream function at 26°N. We construct a distribution of 12-year AMOC trends based on all available 12-year trends of the AMOC Index at 26°N sampled from each model's control simulation (Figure 1a). The information for CMIP3 and CMIP5 control simulations used in this study is provided in Tables S1 and S2 in the supporting information. In this study, the low frequency signal refers to 10-year low pass filtered anomalies.

To investigate the Atlantic decadal predictability, we apply the analysis method of average predictability time (APT; Srivastava & DelSole, 2016) to the North Atlantic SST/surface temperature simulated in CMIP5/CMIP3 models. Predictability is estimated from a linear prediction model that predicts the future states of a field $\mathbf{X}$ based on its current state, using a linear regressed prediction operator estimated from the least square method and applied to multimodel control simulations. Specifying weights $\mathbf{q}$ to each spatial dimension of $\mathbf{X}$ to form a linear combination of $\mathbf{X}$, that is, $\mathbf{q}^T\mathbf{X}$, the predictability at lead time τ can be quantified by the fractional variance ($R^2(\tau)$, that is, $(R(\tau))^2$) calculated by this linear prediction model. Here $R(\tau)$ represents the correlation between the predicted and actual states of $\mathbf{q}^T\mathbf{X}(t + \tau)$. The APT depends on the sum of $R^2(\tau)$ accumulated over lead times of up to about 10 years, at which point $R^2(\tau)$ approaches zero. By maximizing APT, we can solve for the leading eigenvalue and its associated eigenvector (corresponding to the largest APT and the associated weights $\mathbf{q}$ for calculating the most predictable component $\mathbf{q}^T\mathbf{X}$, respectively). Further details are provided in the supporting information.

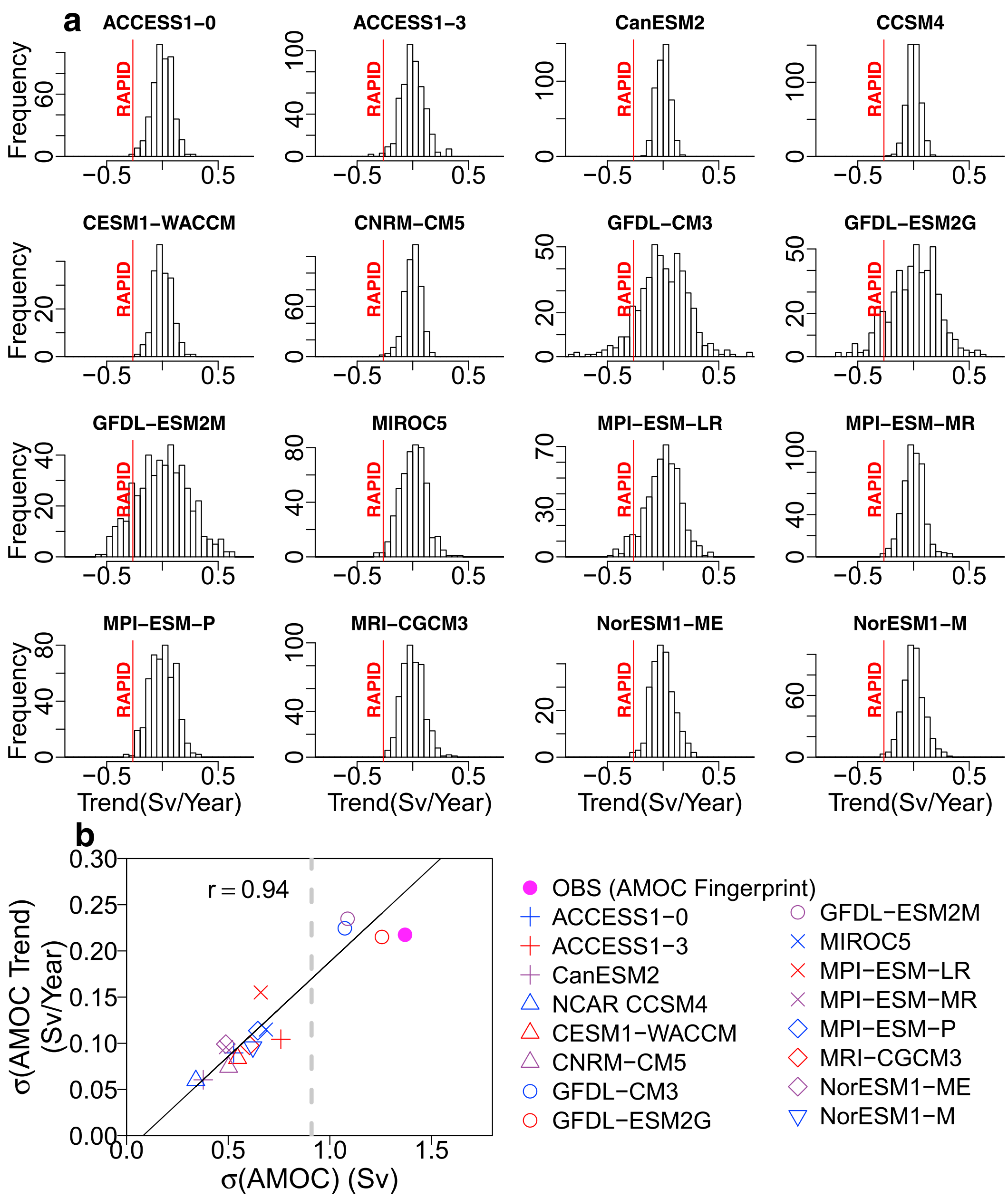

Figure 1. The 12-year Atlantic Meridional Overturning Circulation (AMOC) trend distribution and its relationship with low-frequency AMOC variability. (a) Twelve-year AMOC trend (Sv/yr) distribution from each Coupled Model Intercomparison Project Phase 5 (CMIP5) control simulation and the observed 12-year trend (red line) of the RAPID AMOC Index for the period 2004–2015. (b) Scatterplot of the standard deviations of 12-year AMOC trends versus the amplitudes of low-frequency AMOC variability (i.e., standard deviations of the 10-year low-pass filtered AMOC anomalies) in CMIP5 control simulations. The solid black line shows the linear fit between them. The correlation (r = 0.94) between them is statistically significant ($p < 0.01$). Also included are estimates of the amplitude of low-frequency AMOC variability and the standard deviation of 12-year AMOC trends for observations (magenta dot), inferred from the reconstructed AMOC Index at 26°N using the observed AMOC fingerprint. The gray dashed line separates the models into two groups with stronger (σ(AMOC) > 0.91 Sv) and weaker (σ(AMOC) < 0.91 Sv) low-frequency AMOC variability, respectively, based on the amplitudes of low-frequency AMOC variability (σ(AMOC)). Here the separating threshold 0.91 Sv is about 67% of the estimated σ(AMOC) for observations (1.37 Sv).

3. Low-Frequency AMOC Variability in CMIP5 Models and Observations

The RAPID AMOC Index at 26°N shows a decline trend (−0.265 Sv/yr) over the 12-year period of 2004–2015 (Figures 1 and S2a and S3). Using a high-resolution data assimilation product, this decline has been attributed to be part of a decadal/multidecadal AMOC variability and a recovery from the previous AMOC strengthening (Jackson et al., 2016). In contrast, the CMIP5 multiple model mean (MMM), which can be regarded as an external forced response, shows no significant decline trend of the AMOC Index at 26°N over the same period of 2004–2015 (Figure S3). Greenland glacier meltwater is not well represented in most CMIP5 models and may affect AMOC in the coming decades (Bindoff et al., 2013), but it possibly has not yet had a significant impact on AMOC for the period of 2004–2015 (Böning et al., 2016). This result supports the interpretation that the observed AMOC decline trend over the 12-year period of 2004–2015 mainly originated from internal variability.

Most CMIP5 models have a relatively small spread of 12-year AMOC trends in their control simulations, with a range that barely covers the observed 12-year RAPID AMOC decline trend (Figure 1a), indicating that the simulated internal low-frequency AMOC variability might be underestimated in most CMIP5 models. This underestimation is supported by the strong linkage between the spread (standard deviation) of 12-year AMOC trends and the amplitude of low-frequency AMOC variability (i.e., the standard deviation of 10-year low-pass filtered AMOC Index at 26°N) across multiple CMIP5 models (Figure 1b). A linear regression between these two metrics ($r = 0.94$, $p < 0.01$) suggests that smaller spreads of 12-year AMOC trends are associated with smaller amplitudes of low-frequency AMOC variability as expected. Consistently, Roberts et al. (2014) found that most models underestimate the observed AMOC variability at interannual time scales and possibly at decadal time scales as well.

Given the short observational records, reliable direct estimates of the amplitude of low-frequency AMOC variability and the 12-year AMOC trend spread for observations cannot be achieved. Therefore, we infer these metrics based on a reconstructed AMOC Index at 26°N using the much longer record of an observed AMOC fingerprint since 1955 (section 2 and supporting information). Both the inferred amplitude of low-frequency AMOC variability and the standard deviation of 12-year AMOC trends for observations are much higher than those simulated in most CMIP5 models; including the observation data point in Figure 1b has little impact on the linear fitting result. These results consistently suggest that most CMIP5 models underestimate the amplitude of low-frequency AMOC variability.

We divide the multiple CMIP5 models into two groups based on their simulated amplitudes of low-frequency AMOC variability (Figure 1b), that is, groups with stronger and weaker variability, respectively. The amplitudes of low-frequency AMOC variability in the former group are much closer to the estimate for observations. In the next section, we investigate the linkages between low-frequency AMOC variability and the AMV, hemispheric-scale surface air temperature, and Atlantic decadal predictability by comparing the MMM results from these two groups.

4. The Role of the AMOC in the AMV

Figure 2 shows the MMM correlation maps between the AMOC Index at 26°N and key AMV-related variables in the North Atlantic (i.e., SST, SSS, UOHC, UOSC, and F_{SFC}) at low frequency, for the two groups of CMIP5 models, respectively. The MMM correlations are obtained by first calculating the correlation map for each model and then averaging across models within different groups. Calculating correlations from a merged data consisting of all corresponding models gives very similar results. For models with stronger low-frequency AMOC variability, the MMM correlation maps (Figures 2a–2e) reveal that at low frequency a positive AMOC anomaly is associated with a basin-wide horseshoe-shaped warming pattern in the North Atlantic SST, and a dipole pattern with opposite signs in the subpolar North Atlantic and the Gulf Stream region in the extratropical North Atlantic SSS, UOHC, UOSC, and F_{SFC} (i.e., the typical pattern of the AMOC fingerprint; Joyce & Zhang, 2010; Smeed et al., 2018; Yan et al., 2017; Zhang, 2008, 2017; Zhang & Zhang, 2015). The enhanced heat flux released from ocean to atmosphere in the subpolar North Atlantic (Figure 2e) is consistent with increased Atlantic meridional heat transport convergence (Zhang et al., 2016; Zhang & Zhang, 2015). In the subpolar North Atlantic, the AMOC is positively correlated with SST (Figure 2a) and negatively correlated with F_{SFC} (Figure 2e), consistent with the anticorrelation between SST and F_{SFC} (not shown) at low frequency, which is also found in many previous studies (Chafik et al., 2016; Drews & Greatbatch, 2017; Gulev et al., 2013; O'Reilly et al., 2016; Zhang, 2017; Zhang et al., 2016).

In contrast to the spatial SSS pattern that is mainly confined to the extratropical North Atlantic, the horseshoe SST pattern extends into the tropical North Atlantic (Figures 2a and 2b), suggesting the importance of coupled air-sea feedback, such as wind-evaporation-SST feedback or cloud feedback, in the propagation of

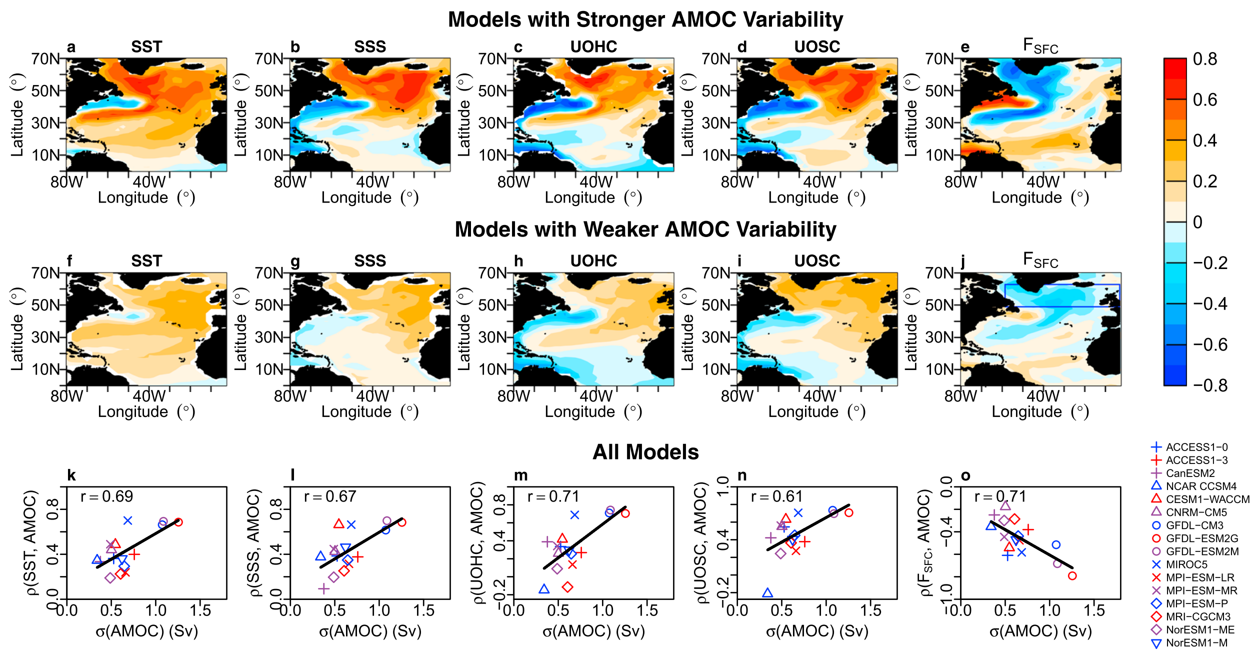

Figure 2. Multiple model mean correlation maps between the 10-year low-pass filtered Atlantic Meridional Overturning Circulation (AMOC) index and Atlantic multidecadal variability (AMV)-related variables (sea surface temperature, sea surface salinity, 700-m UOHC/UOSC, F_{SFC}) and corresponding scatterplots in Coupled Model Intercomparison Project Phase 5 control simulations. (a–e) Models with stronger low-frequency AMOC variability (Figure 1b). (f–j) Models with weaker low-frequency AMOC variability (Figure 1b). (k–o) The scatterplots of amplitudes of the low-frequency AMOC variability versus the low-frequency zero-lag cross correlations between the AMOC Index and the AMV-related variables averaged over the subpolar North Atlantic (blue box in j, 60°W–0°E, 50°N–65°N). The correlation of linear fit (black line) is statistically significant ($p < 0.01$).

the AMV SST signal from the subpolar to the tropical North Atlantic (Brown et al., 2016; Smirnov & Vimont, 2012; Yuan et al., 2016; Zhang et al., 2016; Zhang & Zhang, 2015). These previously proposed coupled air-sea feedbacks are consistent with the positive correlations between the AMOC and F_{SFC} in the tropical North Atlantic (Figure 2e), indicating the indirect influence of AMOC on F_{SFC} and the AMV SST signal in the tropical North Atlantic. Most current fully coupled models are still not capable of simulating these feedbacks and the tropical AMV SST signal adequately (Martin et al., 2014; Yuan et al., 2016).

These results confirm the tight linkage between the AMOC and the AMV-related variables and the coherent multivariate low-frequency variability associated with the AMV (Zhang, 2017). For models with weaker low-frequency AMOC variability (Figures 2f–2j), the MMM correlation maps exhibit similar patterns but with much reduced magnitudes compared to those in Figures 2a–2e, suggesting that the linkage between the AMOC and the AMV-related variables relies on the amplitude of low-frequency AMOC variability. In models with stronger low-frequency AMOC variability, the linkage is much stronger and the AMOC plays a more important role in the AMV-related variables (e.g., SST, SSS, UOHC, UOSC, and F_{SFC}). We further define five indices, that is, the 10-year low-pass filtered SST, SSS, UOHC, UOSC, and F_{SFC} averaged over the subpolar North Atlantic domain. We compare the amplitudes of low-frequency AMOC variability with the corresponding correlations between the AMOC Index and the subpolar North Atlantic SST, SSS, UOHC, UOSC, and F_{SFC} Indices at low frequency across multiple CMIP5 models and identify a significant ($p < 0.01$) linear relationship between them (Figures 2k–2o). Similar results are also obtained across multiple CMIP3 and combined CMIP3/CMIP5 fully coupled models (Figures S4a–S4e and S5a–S5e). These results further support our results based on the correlation map analysis (Figures 2a–2j); that is, stronger low-frequency AMOC variability generally leads to a closer linkage between the AMOC and the AMV-related variables.

5. The Role of the AMOC in the Hemispheric-Scale Surface Air Temperature

The MMM correlation patterns between the subpolar North Atlantic SST Index and surface air temperature around the globe at low frequency (Figures 3a and 3b) exhibit relatively strong correlations mainly in the

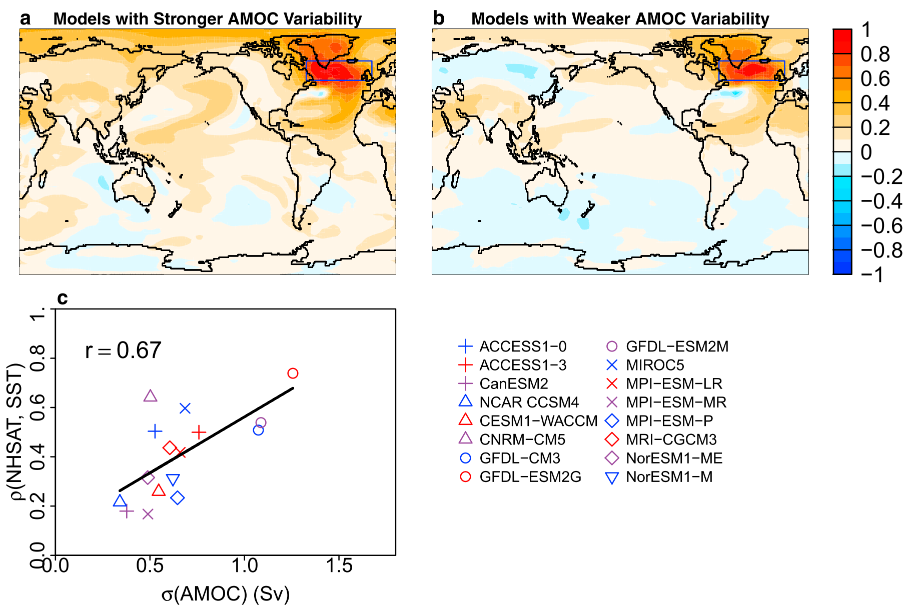

Figure 3. Multiple model mean correlation maps between the 10-year low-pass filtered sea surface temperature (SST) averaged for the subpolar North Atlantic domain (blue box) and the surface air temperature and the corresponding scatterplot in Coupled Model Intercomparison Project Phase 5 control simulations. (a and b) Multiple model mean correlation maps for models with stronger and weaker low-frequency Atlantic Meridional Overturning Circulation (AMOC) variability, respectively. (c) The scatterplot of amplitudes of low-frequency AMOC variability (Sv) versus the low-frequency zero-lag cross correlations between northern hemisphere mean surface air temperature and subpolar North Atlantic area-averaged SST. The correlation of the linear fit (black line) is statistically significant ($p < 0.01$).

northern hemisphere. The magnitudes of the correlations are much higher for models with stronger low-frequency AMOC variability than for models with weaker low-frequency AMOC variability, especially in the tropical North Atlantic, North Pacific, and Arctic. In addition, over middle-high latitudes of Eurasia, the correlations even have generally opposite signs for the two groups of models (Figures 3a and 3b). This suggests that the degree to which the AMV affects the hemispheric-scale surface air temperature variability relies on the amplitude of low-frequency AMOC variability.

Consistent with the correlation maps, the low frequency correlations between the subpolar North Atlantic SST Index and northern hemisphere mean surface air temperature (NHSAT) are significantly ($p < 0.01$) related to the amplitudes of low-frequency AMOC variability across both CMIP3 and CMIP5 fully coupled models (Figures S4f and 3c). The linear fits of the scatterplots also point to a higher correlation with stronger low-frequency AMOC variability. These results suggest that the impact of the AMV on NHSAT indeed relies on the amplitude of low frequency AMOC variability. In addition, results (Figure S6) from both CMIP3 and CMIP5 fully coupled models show that the amplitude of low-frequency variability of global mean surface air temperature and northern hemisphere extratropical (north of 24°N) mean surface air temperature are positively correlated with the amplitude of low-frequency AMOC variability, suggesting that the AMOC may be important for the amplitude of low-frequency global-scale surface air temperature variability.

6. The Role of AMOC in the Atlantic Decadal Predictability

Figure 4a shows that for CMIP5 models with stronger low-frequency AMOC variability, the most predictable pattern of North Atlantic SST resembles the typical simulated AMV SST pattern in CMIP5 models (Ruiz-Barradas et al., 2013; Yuan et al., 2016), with the largest signal over the subpolar North Atlantic. The time series associated with this most predictable pattern is highly correlated with the low-pass filtered subpolar North Atlantic SST Index (with a MMM correlation of 0.85), suggesting that the most predictable component of North Atlantic SST is dominated by the subpolar AMV SST signal. As discussed earlier, most current fully coupled models are still not capable of simulating the tropical AMV SST signal adequately (Martin et al., 2014; Yuan et al., 2016); hence, the tropical AMV SST signal is too weak to appear in the most predictable

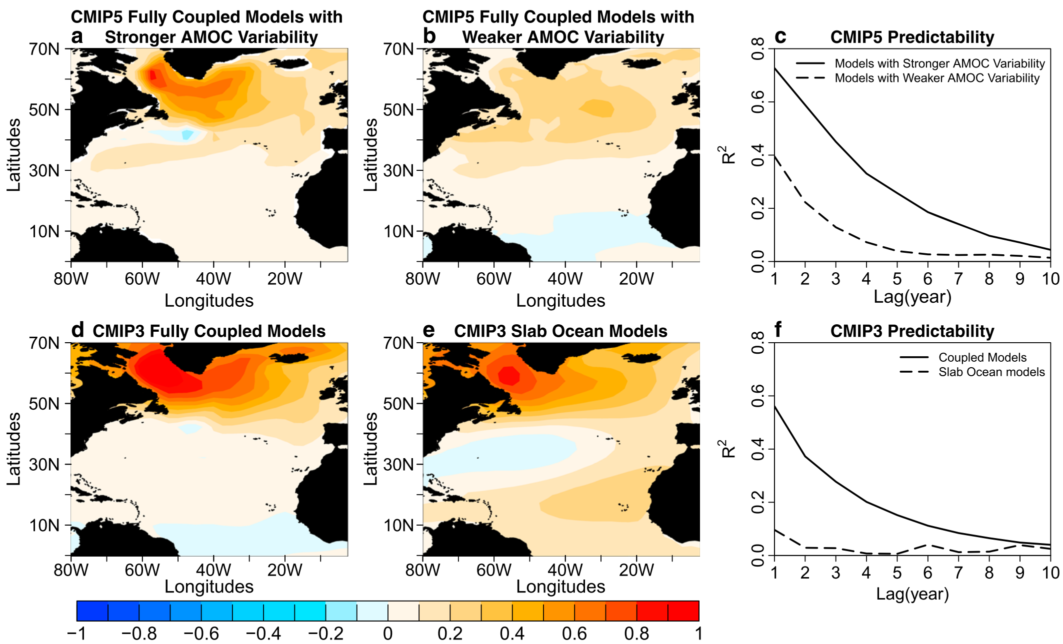

Figure 4. The most predictable patterns and their associated predictability $\mathbf{R^2}(\tau)$ in the North Atlantic. (a and b) The most predictable pattern of sea surface temperature in Coupled Model Intercomparison Project Phase 5 (CMIP5) fully coupled models with (a) stronger or (b) weaker low-frequency Atlantic Meridional Overturning Circulation variability. (c) The predictability $\mathbf{R^2}(\tau)$ associated with the most predictable patterns shown in (a) and (b). (d and e) The most predictable pattern of surface temperature in CMIP3 (d) fully coupled or (e) slab-ocean models. (f) The predictability $\mathbf{R^2}(\tau)$ associated with the most predictable patterns shown in (d) and (e). Each pattern in (a, b, d, and e) has no unit, and the multiplication of the pattern and its corresponding time series (which carries the unit) gives the temperature variations (in °C).

component. For CMIP5 models with weaker low-frequency AMOC variability, the most predictable pattern (Figure 4b) lacks the largest signal in the Labrador Sea. The time series associated with this most predictable pattern is still significantly correlated with the subpolar AMV SST signal (with a MMM correlation of 0.54).

The predictability (R^2) associated with the most predictable component of the North Atlantic SST in both groups of CMIP5 models persists for multiple years and declines gradually (Figure 4c). However, at each lead time, the predictability is much higher in models with stronger low-frequency AMOC variability than in models with weaker low-frequency AMOC variability, with the largest predictability difference up to 0.3 (Figure 4c). This result is consistent with previous studies showing that the AMOC plays an important role in the decadal predictability of the AMV related signal (Hermanson et al., 2014; Msadek et al., 2014; Robson et al., 2012; Trenary & DelSole, 2016; Yang et al., 2013; Yeager et al., 2012; Yeager & Robson, 2017; Zhang, 2017; Zhang & Zhang, 2015) and suggests that the amplitude of low-frequency AMOC variability is crucial for Atlantic decadal predictability.

The most predictable pattern of the North Atlantic surface temperature in CMIP3 fully coupled models (Figure 4d) is similar to that in CMIP5 models with stronger AMOC low-frequency variability (Figure 4a), again with the largest signal over the subpolar North Atlantic. The time series associated with this most predictable pattern is also significantly correlated with the subpolar AMV signal in surface temperature (with a MMM correlation of 0.76). The dominance of the subpolar signal in the most predictable pattern is also consistent with the anomalous ocean heat transport convergence associated with the AMV in the subpolar region in CMIP3 fully coupled models (Zhang et al., 2016) and suggests the important role of ocean dynamics in this most predictable component in fully coupled models. However, in slab ocean models (Figure 4e), the most predictable component shows a tripolar pattern with the same sign in the subpolar and tropical North Atlantic but opposite sign in the subtropical North Atlantic. This tripolar pattern also resembles the relationship between high-pass filtered North Atlantic SST and the atmospheric circulation mode- North Atlantic Oscillation (Delworth et al., 2017; Kushnir, 1994), suggesting that this most predictable component in slab ocean models is mainly induced by the North Atlantic Oscillation-like atmospheric forcing at shorter (interannual) time scales.

Corresponding to the most predictable pattern, the predictability in the slab ocean models declines rapidly at year 1, whereas the predictability in CMIP3 fully coupled models declines gradually and persists for multiple years (Figure 4f). The much higher predictability in fully coupled models than in slab ocean models suggests an important role for ocean dynamics in the Atlantic decadal predictability. The predictability in CMIP3 fully coupled models lies between the predictability in CMIP5 fully coupled models associated with the stronger and weaker low-frequency AMOC variability (Figures 4c and 4f), because the CMIP3 fully coupled models include models with both stronger and weaker low-frequency AMOC variability. The differences in spatial patterns and predictability time scales of the most predictable component between fully coupled and slab ocean models indicate different driving mechanisms in the two types of models.

In summary, the Atlantic decadal predictability is much higher in fully coupled models with stronger low-frequency AMOC variability, declines in fully coupled models with weaker low-frequency AMOC variability, and diminishes greatly in slab ocean models with no AMOC variability. This is consistent with a previous study showing that AMOC variability is a major source of enhanced low-frequency variability and thus decadal persistence in subpolar North Atlantic SST associated with the AMV (Zhang, 2017), in contrast to that obtained from slab ocean models or a simple red noise process (Cane et al., 2017; Clement et al., 2015, 2016).

7. Discussion and Conclusions

Climate models have different mean state biases in the North Atlantic (Ba et al., 2014; Brown et al., 2016; Menary et al., 2015; Wang et al., 2014), which may also play a role in the diverse linkages between the AMOC and the AMV SST signal. Previous studies found that models with smaller mean state biases in the AMOC structure and associated North Atlantic SST/SSS tend to have stronger low-frequency AMOC variability (Drews & Greatbatch, 2016, 2017; Park et al., 2016) and higher multiyear predictability in northern hemisphere surface air temperature (Wu et al., 2018). The underestimated low-frequency AMOC variability is also likely related to modeling biases in the buoyancy forcing affecting low-frequency AMOC variability (Kim et al., 2017). Previous studies indicated that a lack of interannual variability in the wind forcing contributes to the underestimated AMOC variability at interannual time scale (McCarthy et al., 2012; Roberts et al., 2014; Zhao & Johns, 2014). It is also possible that the underestimation of the low-frequency AMOC variability is partially related to a lack of decadal variability in the wind forcing in CMIP models. Our results indicate that the linkage between the AMOC and the AMV, as well as the associated climate impacts and Atlantic decadal predictability, could be substantially hampered in CMIP models due to the underestimation of the amplitude of low-frequency AMOC variability in these models. The results emphasize the importance of simulating realistic low-frequency AMOC variability to achieve potentially more realistic linkages between the AMOC and the AMV and associated climate impacts, and much higher Atlantic decadal predictability.

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References

Ba, J., Keenlyside, N. S., Latif, M., Park, W., Ding, H., Lohmann, K., et al. (2014). A multi-model comparison of Atlantic multidecadal variability. *Climate Dynamics*, *43*(9-10), 2333–2348. https://doi.org/10.1007/s00382-014-2056-1

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., et al. (2013). Detection and attribution of climate change: From global to regional. In T. F. Stocker, et al. (Eds.), *Climate change 2013: The physical science basis* (pp. 867–952). Cambridge, UK: Cambridge University Press.

Böning, C. W., Behrens, E., Biastoch, A., Getzlaff, K., & Bamber, J. L. (2016). Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean. *Nature Geoscience*, *9*(7), 523–527. https://doi.org/10.1038/ngeo2740

Brown, P. T., Lozier, M. S., Zhang, R., & Li, W. (2016). The necessity of cloud feedback for a basin-scale Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, *43*, 3955–3963. https://doi.org/10.1002/2016GL068303

Cane, M. A., Clement, A. C., Murphy, L. N., & Bellomo, K. (2017). Low-pass filtering, heat flux, and Atlantic multidecadal variability. *Journal of Climate*, *30*(18), 7529–7553. https://doi.org/10.1175/JCLI-D-16-0810.1

Chafik, L., Häkkinen, S., England, M. H., Carton, J. A., Nigam, S., Ruiz-Barradas, A., et al. (2016). Global linkages originating from decadal oceanic variability in the subpolar North Atlantic. *Geophysical Research Letters*, *43*, 10,909–10,919. https://doi.org/10.1002/2016GL071134

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

Clement, A., Cane, M. A., Murphy, L. N., Bellomo, K., Mauritsen, T., & Stevens, B. (2016). Response to comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation". *Science*, *350*, 320–324.

DelSole, T., & Tippett, M. K. (2015). Laplacian Eigenfunctions for climate analysis. *Journal of Climate*, *28*(18), 7420–7436. https://doi.org/10.1175/JCLI-D-15-0049.1

Delworth, T. L., Zeng, F., Zhang, L., Zhang, R., Vecchi, G. A., & Yang, X. (2017). The central role of ocean dynamics in connecting the North Atlantic Oscillation to the extratropical component of the Atlantic Multidecadal Oscillation. *Journal of Climate*, *30*(10), 3789–3805. https://doi.org/10.1175/JCLI-D-16-0358.1

Drews, A., & Greatbatch, R. J. (2016). Atlantic multidecadal variability in a model with an improved North Atlantic current. *Geophysical Research Letters*, *43*, 8199–8206. https://doi.org/10.1002/2016GL069815

Drews, A., & Greatbatch, R. J. (2017). Evolution of the Atlantic multidecadal variability in a model with an improved North Atlantic current. *Journal of Climate*, *30*(14), 5491–5512. https://doi.org/10.1175/JCLI-D-16-0790.1

Enfield, D. B., Mestas-Nuñez, A. M., & Trimble, P. J. (2001). The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letters*, *28*(10), 2077–2080. https://doi.org/10.1029/2000GL012745

Goldenberg, S. B., Landsea, C. W., Mestas-Nuñez, A. M., & Gray, W. M. (2001). The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, *293*(5529), 474–479. https://doi.org/10.1126/science.1060040

Gulev, S. K., Latif, M., Keenlyside, N., Park, W., & Koltermann, K. P. (2013). North Atlantic Ocean control on surface heat flux on multidecadal timescales. *Nature*, *499*(7459), 464–467. https://doi.org/10.1038/nature12268

Hermanson, L., Eade, R., Robinson, N. H., Dunstone, N. J., Andrews, M. B., Knight, J. R., et al. (2014). Forecast cooling of the Atlantic subpolar gyre and associated impacts. *Geophysical Research Letters*, *41*, 5167–5174. https://doi.org/10.1002/2014GL060420

Jackson, L. C., Peterson, K. A., Roberts, C. D., & Wood, R. A. (2016). Recent slowing of Atlantic overturning circulation as a recovery from earlier strengthening. *Nature Geoscience*, *9*(7), 518–522. https://doi.org/10.1038/ngeo2715

Joyce, T. M., & Zhang, R. (2010). On the path of the Gulf Stream and the Atlantic Meridional Overturning Circulation. *Journal of Climate*, *23*(11), 3146–3154. https://doi.org/10.1175/2010JCLI3310.1

Keenlyside, N. S., Ba, J., Mecking, J., Omrani, N. E., Latif, M., Zhang, R., & Msadek, R. (2016). North Atlantic multi-decadal variability—Mechanisms and predictability. In C.-P. Chang, et al. (Eds.), *Climate change: Multidecadal and beyond* (pp. 141–158). Singapore: SG, World Scientific.

Kerr, R. A. (2000). A North Atlantic climate pacemaker for the centuries. *Science*, *288*(5473), 1984–1985. https://doi.org/10.1126/science.288.5473.1984

Kim, W. M., Yeager, S., Chang, P., & Danabasoglu, G. (2017). Low-frequency North Atlantic climate variability in the community Earth system model large ensemble. *Journal of Climate*, *31*, 787–813.

Klotzbach, P. J., Gray, W., & Fogarty, C. (2015). Active Atlantic hurricane era at its end? *Nature Geoscience*, *8*(10), 737–738. https://doi.org/10.1038/ngeo2529

Klotzbach, P. J., & Gray, W. M. (2008). Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate*, *21*(15), 3929–3935. https://doi.org/10.1175/2008JCLI2162.1

Knight, J. R., Folland, C. K., & Scaife, A. A. (2006). Climate impacts of the Atlantic multidecadal oscillation. *Geophysical Research Letters*, *33*, L17706. https://doi.org/10.1029/2006GL026242

Kushnir, Y. (1994). Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *Journal of Climate*, *7*(1), 141–157. https://doi.org/10.1175/1520-0442(1994)007<0141:IVINAS>2.0.CO;2

Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., et al. (2012). World Ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters*, *39*, L10603. https://doi.org/10.1029/2012GL051106

Martin, E. R., Thorncroft, C., & Booth, B. B. (2014). The multidecadal Atlantic SST—Sahel rainfall teleconnection in CMIP5 simulations. *Journal of Climate*, *27*(2), 784–806. https://doi.org/10.1175/JCLI-D-13-00242.1

McCarthy, G., Frajka-Williams, E., Johns, W. E., Baringer, M. O., Meinen, C. S., Bryden, H. L., et al. (2012). Observed interannual variability of the Atlantic Meridional Overturning Circulation at 26.5°N. *Geophysical Research Letters*, *39*, L19609. https://doi.org/10.1029/2012GL052933

McCarthy, G. D., Haigh, I. D., Hirschi, J. J. M., Grist, J. P., & Smeed, D. A. (2015). Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature*, *521*(7553), 508–510. https://doi.org/10.1038/nature14491

Menary, M. B., Hodson, D. L., Robson, J. I., Sutton, R. T., Wood, R. A., & Hunt, J. A. (2015). Exploring the impact of CMIP5 model biases on the simulation of North Atlantic decadal variability. *Geophysical Research Letters*, *42*, 5926–5934. https://doi.org/10.1002/2015GL064360

Msadek, R., Delworth, T. L., Rosati, A., Anderson, W., Vecchi, G., Chang, Y. S., et al. (2014). Predicting a decadal shift in North Atlantic climate variability using the GFDL forecast system. *Journal of Climate*, *27*(17), 6472–6496. https://doi.org/10.1175/JCLI-D-13-00476.1

O'Reilly, C. H., Huber, M., Woollings, T., & Zanna, L. (2016). The signature of low frequency oceanic forcing in the Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, *43*, 2810–2818. https://doi.org/10.1002/2016GL067925

Park, T., Park, W., & Latif, M. (2016). Correcting North Atlantic sea surface salinity biases in the Kiel climate model: Influences on ocean circulation and Atlantic multidecadal variability. *Climate Dynamics*, *47*(7-8), 2543–2560. https://doi.org/10.1007/s00382-016-2982-1

Roberts, C. D., Jackson, L., & McNeall, D. (2014). Is the 2004–2012 reduction of the Atlantic Meridional Overturning Circulation significant? *Geophysical Research Letters*, *41*, 3204–3210. https://doi.org/10.1002/2014GL059473

Robson, J., Ortega, P., & Sutton, R. (2016). A reversal of climatic trends in the North Atlantic since 2005. *Nature Geoscience*, *9*(7), 513–517. https://doi.org/10.1038/ngeo2727

Robson, J. I., Sutton, R. T., & Smith, D. M. (2012). Initialized decadal predictions of the rapid warming of the North Atlantic Ocean in the mid 1990s. *Geophysical Research Letters*, *39*, L19713. https://doi.org/10.1029/2012GL053370

Ruiz-Barradas, A., Nigam, S., & Kavvada, A. (2013). The Atlantic Multidecadal Oscillation in twentieth century climate simulations: Uneven progress from CMIP3 to CMIP5. *Climate Dynamics*, *41*(11-12), 3301–3315. https://doi.org/10.1007/s00382-013-1810-0

Semenov, V. A., Latif, M., Dommenget, D., Keenlyside, N. S., Strehz, A., Martin, T., & Park, W. (2010). The impact of North Atlantic-Arctic multidecadal variability on Northern Hemisphere surface air temperature. *Journal of Climate*, *23*(21), 5668–5677. https://doi.org/10.1175/2010JCLI3347.1

Smeed, D. A., Josey, S. A., Beaulieu, C., Johns, W. E., Moat, B. I., Frajka-Williams, E., et al. (2018). The North Atlantic Ocean is in a state of reduced overturning. *Geophysical Research Letters*, *45*, 1527–1533. https://doi.org/10.1002/2017GL076350

Smeed, D. A., McCarthy, G. D., Cunningham, S. A., Frajka-Williams, E., Rayner, D., Johns, W. E., et al. (2014). Observed decline of the Atlantic Meridional Overturning Circulation 2004–2012. *Ocean Science*, *10*(1), 29–38. https://doi.org/10.5194/os-10-29-2014

Smeed, D. A., McCarthy, G. D., Rayner, D., Moat, B. I., Johns, W. E., Barringer, M. O., & Meinen, C. S. (2016). Atlantic Meridional Overturning Circulation observed by the RAPID-MOCHA-WBTS (RAPID-Meridional Overturning Circulation and heatflux array-western boundary time series) array at 26N from 2004 to 2015. British Oceanographic Data Centre - Natural Environment Research Council, UK.

Smirnov, D., & Vimont, D. J. (2012). Extratropical forcing of tropical Atlantic variability during boreal summer and fall. *Journal of Climate*, *25*(6), 2056–2076. https://doi.org/10.1175/JCLI-D-11-00104.1

Srivastava, A., & DelSole, T. (2016). Decadal predictability without ocean dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 2177–2182.

Sutton, R. T., & Hodson, D. L. (2005). Atlantic Ocean forcing of North American and European summer climate. *Science*, *309*(5731), 115–118. https://doi.org/10.1126/science.1109496

Trenary, L., & DelSole, T. (2016). Does the Atlantic Multidecadal Oscillation get its predictability from the Atlantic Meridional Overturning Circulation? *Journal of Climate*, *29*(14), 5267–5280. https://doi.org/10.1175/JCLI-D-16-0030.1

Wang, C., Zhang, L., Lee, S. K., Wu, L., & Mechoso, C. R. (2014). A global perspective on CMIP5 climate model biases. *Nature Climate Change*, *4*(3), 201–205. https://doi.org/10.1038/nclimate2118

Wu, Y., Park, T., Park, W., & Latif, M. (2018). North Atlantic climate model bias influence on multiyear predictability. *Earth and Planetary Science Letters*, *481*, 171–176. https://doi.org/10.1016/j.epsl.2017.10.012

Yan, X., Zhang, R., & Knutson, T. R. (2017). The role of Atlantic overturning circulation in the recent decline of Atlantic major hurricane frequency. *Nature Communications*, *8*(1), 1695. https://doi.org/10.1038/s41467-017-01377-8

Yang, X., Rosati, A., Zhang, S., Delworth, T. L., Gudgel, R. G., Zhang, R., et al. (2013). A predictable AMO-like pattern in the GFDL fully coupled ensemble initialization and decadal forecasting system. *Journal of Climate*, *26*(2), 650–661. https://doi.org/10.1175/JCLI-D-12-00231.1

Yeager, S., Karspeck, A., Danabasoglu, G., Tribbia, J., & Teng, H. (2012). A decadal prediction case study: Late twentieth-century North Atlantic Ocean heat content. *Journal of Climate*, *25*(15), 5173–5189. https://doi.org/10.1175/JCLI-D-11-00595.1

Yeager, S. G., & Robson, J. I. (2017). Recent progress in understanding and predicting Atlantic decadal climate variability. *Current Climate Change Reports*, *3*(2), 112–127. https://doi.org/10.1007/s40641-017-0064-z

Yuan, T., Oreopoulos, L., Zelinka, M., Yu, H., Norris, J. R., Chin, M., et al. (2016). Positive low cloud and dust feedbacks amplify tropical North Atlantic Multidecadal Oscillation. *Geophysical Research Letters*, *43*, 1349–1356. https://doi.org/10.1002/2016GL067679

Zhang, J., & Zhang, R. (2015). On the evolution of Atlantic Meridional Overturning Circulation fingerprint and implications for decadal predictability in the North Atlantic. *Geophysical Research Letters*, *42*, 5419–5426. https://doi.org/10.1002/2015GL064596

Zhang, L., & Wang, C. (2013). Multidecadal North Atlantic sea surface temperature and Atlantic Meridional Overturning Circulation variability in CMIP5 historical simulations. *Journal of Geophysical Research: Oceans*, *118*, 5772–5791. https://doi.org/10.1002/jgrc.20390

Zhang, R. (2008). Coherent surface-subsurface fingerprint of the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters*, *35*, L20705. https://doi.org/10.1029/2008GL035463

Zhang, R. (2010). Latitudinal dependence of Atlantic Meridional Overturning Circulation (AMOC) variations. *Geophysical Research Letters*, *37*, L16703. https://doi.org/10.1029/2010GL044474

Zhang, R. (2017). On the persistence and coherence of subpolar sea surface temperature and salinity anomalies associated with AMOC multidecadal variability. *Geophysical Research Letters*, *44*(15), 7865–7875. https://doi.org/10.1002/2017GL074342

Zhang, R., & Delworth, T. L. (2006). Impact of Atlantic Multidecadal Oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophysical Research Letters*, *33*, L17712. https://doi.org/10.1029/2006GL026267

Zhang, R., Delworth, T. L., & Held, I. M. (2007). Can the Atlantic Ocean drive the observed multidecadal variability in Northern Hemisphere mean temperature? *Geophysical Research Letters*, *34*, L02709. https://doi.org/10.1029/2006GL028683

Zhang, R., Delworth, T. L., Rosati, A., Anderson, W. G., Dixon, K. W., Lee, H.-C., & Zeng, F. (2011). Sensitivity of the North Atlantic Ocean circulation to an abrupt change in the Nordic Sea overflow in a high resolution global coupled climate model. *Journal of Geophysical Research*, *116*, C12024. https://doi.org/10.1029/2011JC007240

Zhang, R., Sutton, R., Danabasoglu, G., Delworth, T. L., Kim, W. M., Robson, J., & Yeager, S. G. (2016). Comment on "The Atlantic Multidecadal Oscillation without a role for ocean circulation". *Science*, *352*(6293), 1527. https://doi.org/10.1126/science.aaf1660

Zhao, J., & Johns, W. (2014). Wind-forced interannual variability of the Atlantic Meridional Overturning Circulation at 26.5°N. *Journal of Geophysical Research: Oceans*, *119*, 2403–2419. https://doi.org/10.1002/2013JC009407