AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL072681

Key Points:
- In climate model simulations the global signal must be removed to reveal important AMO-related features outside the North Atlantic
- Previous studies based on the North Atlantic SST may underestimate model performance in simulating the AMO-related worldwide impacts
- The observed and model-simulated global mean surface temperature variations could be dominated by different climate processes

Supporting Information:
- Supporting Information S1

Correspondence to:
K. Lyu,
lyuk1@uci.edu

Citation:
Lyu, K., and J.-Y. Yu (2017), Climate impacts of the Atlantic Multidecadal Oscillation simulated in the CMIP5 models: A re-evaluation based on a revised index, *Geophys. Res. Lett.*, *44*, doi:10.1002/2017GL072681.

Received 17 JAN 2017
Accepted 10 APR 2017
Accepted article online 13 APR 2017

Climate impacts of the Atlantic Multidecadal Oscillation simulated in the CMIP5 models: A re-evaluation based on a revised index

Kewei Lyu[1] and Jin-Yi Yu[1]

[1]Department of Earth System Science, University of California, Irvine, California, USA

Abstract The Atlantic Multidecadal Oscillation (AMO) has pronounced influences on weather and climate across the globe. This study provides a direct comparison of the observed AMO-related surface temperature and precipitation anomalies to those simulated in the Coupled Model Intercomparison Project Phase 5 (CMIP5) models. It is found that the model-simulated AMO-related features are obscured by the global signal in some key regions if the North Atlantic sea surface temperature (SST) itself is used to represent the AMO as in previous studies. After the global mean SST is removed from the North Atlantic SST, the CMIP5 models show substantially better agreement with the observations in terms of the AMO-related worldwide impacts, such as the Pacific SST and the rainfall over the United States and India. These results suggest the removal of the global signal or signals originating in other ocean basins is a necessary procedure to uncover the AMO features in climate model simulations.

1. Introduction

Sea surface temperatures (SSTs) in the North Atlantic exhibit a basin-scale fluctuation on multidecadal time scales known as the Atlantic Multidecadal Oscillation (AMO) [*Kerr*, 2000]. The underlying mechanisms for the observed AMO are still a subject of debate. The AMO could arise from internal dynamics of the climate system, given the existence of AMO-like spatial-temporal features in preindustrial proxy-based climate reconstructions and long climate model simulations with constant external forcing [*Delworth and Mann*, 2000; *Knight et al.*, 2005]. This "internally generated" AMO has been attributed to changes in northward heat transport by the Atlantic meridional overturning circulation (AMOC) [e.g., *Delworth et al.*, 1993; *O'Reilly et al.*, 2016; *Zhang et al.*, 2016] or the middle-latitude atmospheric stochastic forcing [*Clement et al.*, 2015]. Besides these unforced climate dynamics, external forcings, either anthropogenic or naturally occurring (e.g., aerosols and volcanos), may also contribute to the observed AMO [*Otterå et al.*, 2010; *Booth et al.*, 2012]. A number of studies suggested that the observed AMO should be viewed as a combination of both internal variability and responses to external forcings, which have somewhat distinct signatures though it is still challenging to clearly distinguish them [*Knight*, 2009; *Ting et al.*, 2009, 2014; *DelSole et al.*, 2011; *Terray*, 2012; *Zhang et al.*, 2013; *Lyu et al.*, 2015].

Although the primary drivers remain unclear [e.g., *Keenlyside et al.*, 2015], as one of the most important climate modes, the AMO has been widely linked to prominent regional climate anomalies that can have tremendous socioeconomic consequences. The AMO can modulate Atlantic hurricane activity [*Goldenberg et al.*, 2001], disrupt the North American and European summer climate [*Sutton and Hodson*, 2005], and change rainfall over the United States [*Enfield et al.*, 2001], the Sahel [*Folland et al.*, 1986], and northeast Brazil [*Knight et al.*, 2006]. The AMO impacts are not confined in and around the Atlantic but have been found worldwide, e.g., in the Asian and Indian monsoon [*Zhang and Delworth*, 2005], China summer drought pattern [*Qian et al.*, 2014], Siberian rainfall [*Sun et al.*, 2015], low-frequency El Niño–Southern Oscillation modulations [*Dong et al.*, 2006; *Timmermann et al.*, 2007; *Yu et al.*, 2015], and Antarctic sea ice [*Li et al.*, 2014]. In light of its connections to these high-impact regional climate phenomena, a realistic simulation of the AMO and its climate impacts is of great importance for better understanding the historical climate record and also for improving near-term climate predictions.

Several studies have examined whether global climate models can simulate the AMO and its climate impacts. *Ting et al.* [2011, 2014] found that the AMO SST patterns and associated tropical Atlantic precipitation anomalies simulated in the Coupled Model Intercomparison Project Phase 3 (CMIP3) models resemble those in the observations. However, they also found that the CMIP3 models cannot simulate the AMO-related SST anomalies in the tropical Pacific and the precipitation anomalies in some other regions such as North America, India, and Australia. The current generation global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) can also simulate AMO-like patterns in the North Atlantic but may underestimate its amplitude and multidecadal component [*Zhang and Wang*, 2013; *Peings et al*., 2016]. *Kavvada et al*. [2013] and *Ruiz-Barradas et al*. [2013] suggested that the CMIP5 models cannot simulate some detailed features of the AMO as well as its hydroclimate impacts on neighboring continents. *Han et al*. [2016] found that the AMO-related climate signals around the North Atlantic in the CMIP5 models are fairly consistent with the observations, while major disagreements exist in other regions. The failures of climate models to reproduce some observed AMO-related climate phenomena raise questions about the robustness of their linkages with the AMO that have been inferred from short instrumental records and also cast doubt on the capability of current global climate models to represent and predict these and perhaps other climate impacts.

In this study, we argue that these previous studies using the North Atlantic-averaged SST (NASST) to represent the AMO failed to account for a global signal that largely masks the AMO-related large-scale features. Here we present a new estimate of the AMO-related worldwide impacts simulated in the CMIP5 models based on a revised AMO index constructed by simply subtracting the time-dependent global mean SST (GMSST) from the NASST. This new estimate shows better agreement with its observed counterpart than that based on the NASST only, implying a better performance of global climate models than suggested in previous studies.

2. Observations and CMIP5 Models

Gridded land surface temperatures and precipitation at a horizontal resolution of 0.5° for the period 1901–2014 from the Climatic Research Unit time series data set version 3.23 (CRU TS 3.23) [*Harris et al*., 2014] are used to characterize the observed AMO impacts. The SST data on a 1° longitude-latitude grid are from the Hadley Centre SST data set (HadISST) [*Rayner et al*., 2003]. We analyzed the 26 CMIP5 models for which preindustrial runs of at least 400 years are available (supporting information Table S1). The preindustrial runs, which have considerably larger samples of AMO cycles than historical runs and observations, were mainly analyzed here to examine whether the AMO climate impacts seen in the comparatively short observational record are robust or not. The choice of analyzing the preindustrial runs also excludes possible contributions from external forcing, thus allowing an investigation of the AMO that is only internally generated within the climate system.

3. Results

The NASST index was calculated as the 10 year low-pass-filtered area-weighted average of SST over 0°–70°N, 80°W–0° (supporting information Figure S1). The NASST was linearly detrended to remove the long-term warming signal. Since the anthropogenic effects do not have to be linear, a linear detrending may not fully remove the imprint of anthropogenic forcing on the NASST. Considering that the observed NASST variations result from a combination of a background global signal and a regional signal with North Atlantic origins, written as

$$\mathrm{NASST} = \mathrm{GMSST} + \mathrm{AMO}^*, \tag{1}$$

Trenberth and Shea [2006] proposed a revised AMO index by subtracting the GMSST time series from the NASST. Here the GMSST serves as a proxy for the nonstationary anthropogenic signal, although it still has contributions from the internal climate variability. Given that the GMSST may not be sufficient to represent the North Atlantic local expressions of the external forcing, another way to derive the AMO index is by removing multimodel ensemble estimates of the forced component of NASST variations from the observed NASST [*Ting et al*., 2009]. *Deser et al*. [2010] and *Peings et al*. [2016] showed that there is large consistency among the temporal evolutions of these three types of AMO index, although they differ substantially in the degree to which the recent North Atlantic warming is attributed to external forcing or the internal AMO. We found the correlation between the filtered and detrended NASST and AMO* (i.e., NASST minus GMSST) in observations is as high as 0.88. Therefore, as shown below, regression patterns onto the filtered

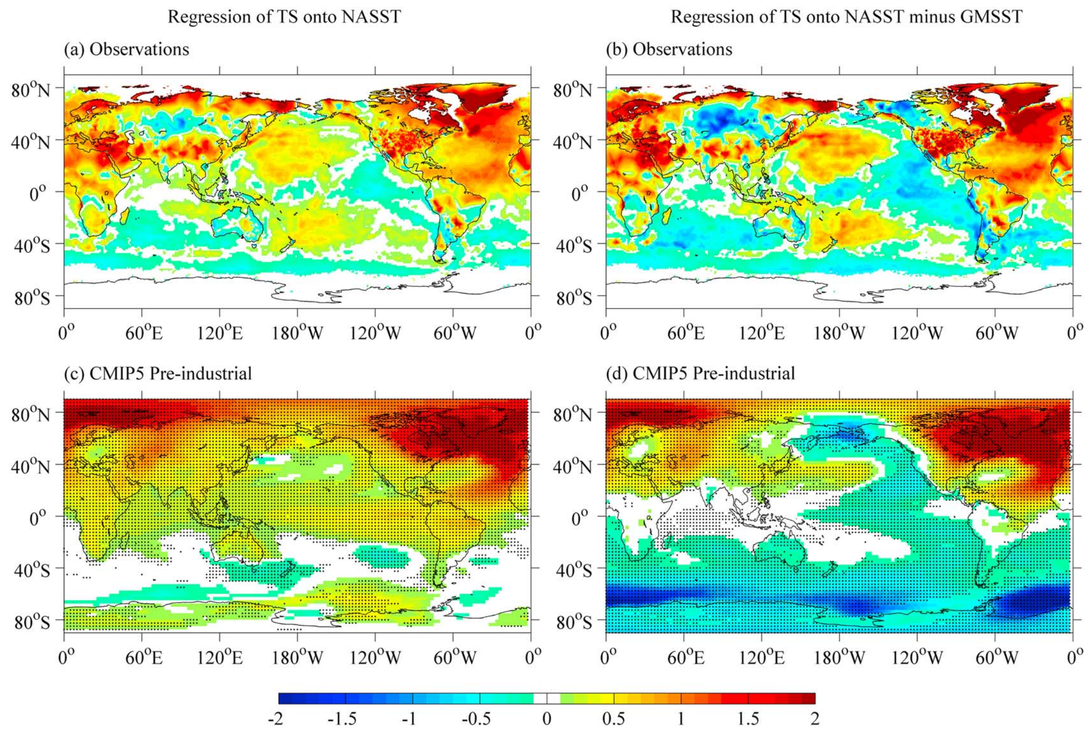

Figure 1. Regression patterns in annual surface temperature (°C per 1° of North Atlantic warming) onto the 10 year low-pass-filtered and detrended (a and c) NASST and (b and d) NASST minus GMSST: observations Figures 1a and 1b and multimodel mean patterns Figures 1c and 1d from the CMIP5 preindustrial runs, with stippling indicating that at least two thirds of the models (18 out of 26) agree on the sign of regression values.

and detrended NASST and AMO* in observations exhibit few differences and also share similar features to those based on the NASST with the model-estimated forced signal removed [*Ting et al*., 2011].

We examined the AMO-related surface temperature anomalies by regressing observed SSTs and land surface temperatures and simulated surface air temperatures onto the filtered and detrended NASST and AMO*. The AMO has a comma-like SST structure with the largest anomalies in the subpolar North Atlantic extending into the subtropics in the eastern portion of the basin, which is well simulated by the CMIP5 models whether the regressions are based on NASST or AMO* (Figure 1). The imprints of the AMO on the SST field, though centered in the North Atlantic, extend well beyond. In observations, the positive AMO phase is accompanied by cooling in the South Atlantic, a zonally elongated band in the Southern Ocean, and the tropical Pacific as well as warming in northwest and southwest Pacific (Figures 1a and 1b). Similar features can be seen in the recent two AMO phase shift events during the 1960s and the 1990s (supporting information Figure S2) and also occur for both winter and summer (supporting information Figures S3 and S4). The observed AMO-related Pacific SST anomalies are generally consistent with responses seen in coupled model experiments using prescribed AMO SST forcing in the North Atlantic [*Dong et al*., 2006; *Kang et al*., 2014; *Kucharski et al*., 2016; *Lyu et al*., 2017; *Ruprich-Robert et al*., 2017]. They are also consistent with the responses to changes in AMOC intensity [*Zhang and Delworth*, 2005; *Timmermann et al*., 2007; *Wu et al*., 2008] and agree with a recent analysis by *Barcikowska et al*. [2017]. *McGregor et al*. [2014] and *Li et al*. [2015] suggested that the recent tropical Atlantic warming contributes to the tropical Pacific cooling during the past several decades.

The multimodel averaged regression patterns onto the NASST in the CMIP5 preindustrial simulations show extensive warming over much of the globe (Figure 1c), in clear contrast to the observed anomalies outside the North Atlantic (Figures 1a and 1b). In the Pacific, the simulated NASST regressions even have SST anomalies of nearly opposite sign to the observations, with warming in the tropical Pacific and insignificant cooling at middle latitudes (Figure 1c). In contrast, when regressing onto the AMO*, i.e., NASST minus GMSST, we found that most of the observed AMO-related SST features outside the North Atlantic can be clearly seen in the CMIP5 preindustrial simulations, including cooling in the South Atlantic, the Southern Ocean, and

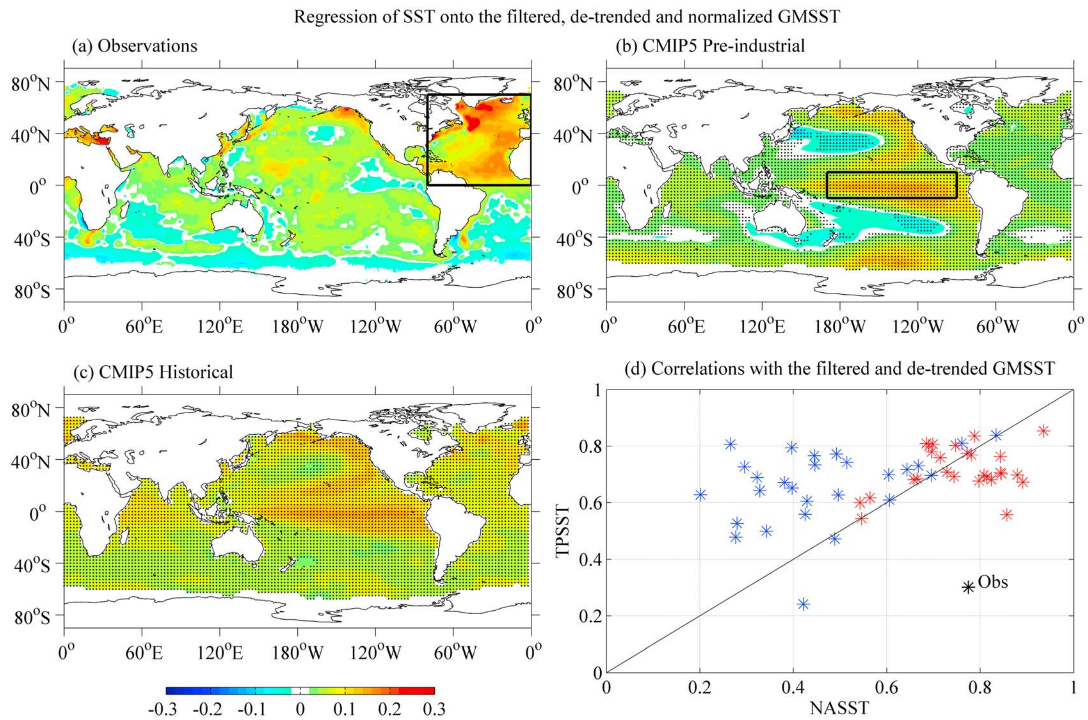

Figure 2. Regression patterns in the SST (°C) onto the normalized, 10 year low-pass-filtered and detrended GMSST: (a) observations and (b, c) multimodel mean patterns from the CMIP5 preindustrial or historical runs, with stippling indicating that at least two thirds of the models (18 out of 26) agree on the sign of regression values. (d) Correlations of the NASST and TPSST with the GMSST in observations and the CMIP5 preindustrial and historical runs. The black boxes in Figures 2a and 2b indicate the NASST and TPSST regions.

the tropical Pacific as well as warming in the extratropical Pacific, although the southwestern Pacific warming is not consistently reproduced (Figure 1d).

It appears that in order to identify "true" surface temperature anomalies associated with the AMO in climate model simulations, the GMSST has to be removed from the NASST before the regressions are performed (Figures 1c and 1d), although this is not a necessary procedure for observations (Figures 1a and 1b). To explain such difference, we investigated the causes of GMSST variations in observations and the CMIP5 simulations. Regressions onto the 10 year low-pass-filtered and detrended GMSST in observations show the largest anomalies are in the North Atlantic and closely resemble the AMO (Figure 2a), consistent with previous studies showing that the variations in the observed global mean surface temperature have a multidecadal component that is largely in phase with the NASST variations [*Schlesinger and Ramankutty*, 1994; *Wu et al*., 2011; *Zhou and Tung*, 2013; *Chylek et al*., 2014]. The observed GMSST warming is accompanied not only by considerable North Atlantic warming but also cooling in the South Atlantic and the Southern Ocean (Figure 2a), implying a possible signature of the AMOC. *Chen and Tung* [2014] found substantial ocean heat uptake occurred in the Atlantic and the Southern Ocean during the recent global mean surface temperature warming slowdown (i.e., "hiatus"), further supporting the important role for the AMOC in global heat redistribution. Therefore, the observed multidecadal GMSST variations may be partly due to internal AMO variability, which implies that removing the GMSST from the NASST in observations would result in the loss of part of the AMO signal, as also commented on by *Enfield and Cid-Serrano* [2010]. However, for the purposes of identifying the AMO large-scale teleconnections rather than the AMO itself, removing the GMSST does not affect the observational results much (Figures 1a and 1b), since the regional signals associated with observed GMSST variations are primarily located in the North Atlantic with much weaker expressions in other regions (Figure 2a). Therefore, in observations, subtracting the GMSST-related signal (Figure 2a) from the NASST-related signal (Figure 1a) gives very similar patterns both in and outside the North Atlantic (Figure 1b).

The removal of GMSST from NASST proposed by *Trenberth and Shea* [2006] was intended to expunge the anthropogenic effects from observations. One may question why this procedure is necessary for climate model preindustrial simulations that contain no externally forced signals (Figures 1c and 1d). The multimodel averaged regression patterns onto the filtered and detrended GMSST in the CMIP5 preindustrial simulations exhibit prominent SST anomalies in the tropical Pacific and opposite-signed anomalies in the midlatitude North and South Pacific (Figure 2b), which closely resemble the Interdecadal Pacific Oscillation pattern [e.g., *Lyu et al*., 2016]. Such model evidence suggests an important role for Pacific low-frequency climate variability in the recent global mean surface warming slowdown [e.g., *Kosaka and Xie*, 2013; *Trenberth and Fasullo*, 2013; *England et al*., 2014; *Maher et al*., 2014; *Song et al*., 2014]. To facilitate a direct comparison between observations and models, we calculated the correlations of the GMSST with the NASST and tropical Pacific SST (TPSST) on time scales longer than 10 years in observations and the CMIP5 preindustrial simulations. While the observed GMSST is highly correlated with the NASST (~0.77), most of the CMIP5 preindustrial runs produce unforced GMSST variations that are more associated with the TPSST than with the NASST (Figure 2d). It seems that the GMSST variations in observations and the preindustrial simulations are likely the result of different climate processes that have their emphasis in different ocean basins (Figures 2a and 2b). Regressions onto the NASST (Figure 1c) capture the joint effects of both the AMO-related signals (Figure 1d) and the GMSST-related signals (Figure 2b), with the latter being mainly induced by the Pacific low-frequency variability in the preindustrial simulations. Since the GMSST-related SST anomalies outside the North Atlantic are nearly opposite in sign compared to those associated with the AMO* in the preindustrial simulations (Figure 2b versus Figure 1d), a combination of these two signals, i.e., regressions onto the NASST (Figure 1c), easily mask the AMO-related signals that are of Atlantic origin. Therefore, for climate model preindustrial simulations, the AMO-related SST features outside the North Atlantic can only be revealed after the global signal is factored out (Figure 1d).

We repeated our analysis using the CMIP5 historical simulations, in which the GMSST variations have additional contributions from the changing external forcings as in observations [*Sutton et al*., 2015]. In the historical simulations, the correlations between the filtered and detrended GMSST and NASST are larger and closer to the observed value than in the preindustrial simulations (Figure 2d). However, the GMSST is still highly correlated with TPSST (Figure 2d), with the GMSST regression patterns also showing the largest SST anomalies in the tropical Pacific (Figure 2c). Therefore, as in the preindustrial simulations, the removal of the GMSST from the NASST also helps to reveal the AMO-related large-scale features from the global signal in the historical simulations, although such a simple procedure cannot fully account for the externally forced NASST signal (supporting information Figure S5). The inconsistency between the GMSST regression patterns in observations (Figure 2a) and the historical simulations (Figure 2c) poses a challenge to our understanding of the variations in global mean surface temperature. The possible reasons for this difference could be that the climate models may overestimate the role of Pacific climate processes in modulating the GMSST, or the impacts of unforced Pacific climate variability on the GMSST in the real world are dominated by the impacts of varying external forcings, or the climate models cannot realistically represent global and regional climate responses to the external forcings.

The precipitation data were also regressed onto the filtered and detrended NASST and AMO* in both observations and the CMIP5 simulations (Figure 3; see the supporting information Figure S6 for annual mean regression patterns). We also checked the precipitation anomalies associated with the recent two AMO phase shift events (supporting information Figure S7). Compared to the observations which are for land only, the climate model simulations enable us to investigate the large-scale patterns that influence the precipitation over land and the possible causes. In the tropical Atlantic, the CMIP5 multimodel mean regression patterns show a north-south dipole of precipitation anomalies straddling the climatological precipitation maxima. In December–February (DJF), the westward extension of this anomalous rainfall dipole over the land leads to increased rainfall over the northern South America and a reduction in rainfall over the rest of South America including northeast Brazil [*Knight et al*., 2006] and southeastern South America [*Seager et al*., 2010] (Figures 3a–3d). In June–August (JJA), this dipolar structure moves northward with the climatological Intertropical Convergence Zone (ITCZ) location, also leading to increased rainfall over Central America, the Caribbean, and western Africa including the Sahel region (Figures 3e–3h). The linkage between the AMO and the Sahel summer rainfall has been widely reported based on observations and model simulations [*Knight et al*., 2006; *Zhang and Delworth*, 2006; *Mohino et al*., 2011; *Wang et al*., 2012] as well as paleoclimate reconstructions [*Shanahan et al*., 2009]. *Martin et al*. [2014] suggested that the AMO-related Sahel rainfall anomalies are weak in the CMIP5 simulations (Figures 3g and 3h) due to insufficient SST forcing in the

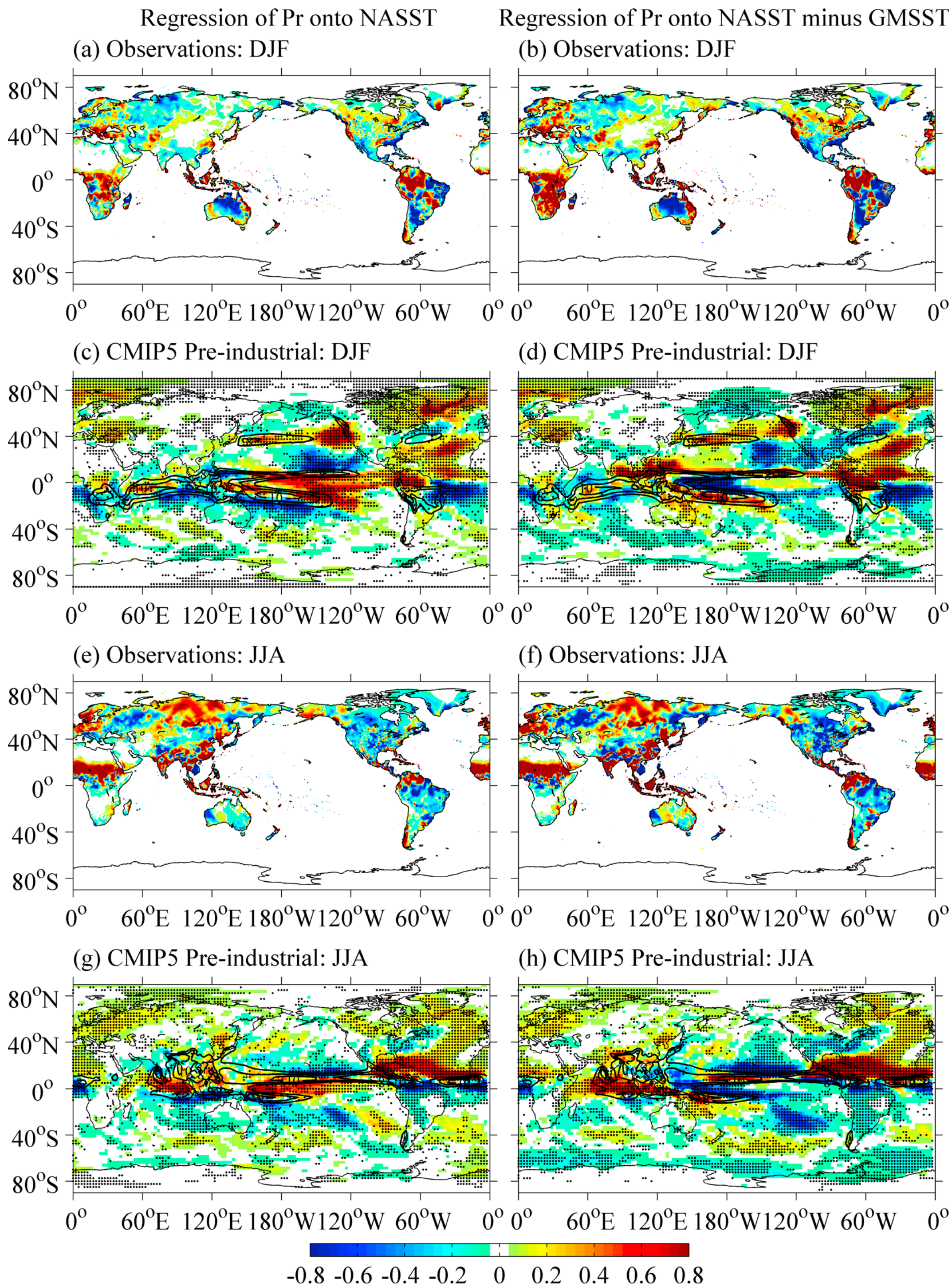

Figure 3. Regression patterns in DJF and JJA precipitation (mm/d per 1° of North Atlantic warming) onto the 10 year low-pass-filtered and detrended (a, c, e, and g) NASST and (b, d, f, and h) NASST minus GMSST: observations Figures 3a, 3b, 3e, and 3f and multimodel mean patterns Figures 3c, 3d, 3g, and 3h from the CMIP5 preindustrial runs, with stippling indicating that at least two thirds of the models (18 out of 26) agree on the sign of regression values.

tropical North Atlantic and Mediterranean. Regressions onto either the NASST or AMO* in the CMIP5 simulations reproduce these observed precipitation anomalies in the tropical Atlantic (Figure 3), which are directly induced by a meridional migration of the Atlantic ITCZ as a response to the anomalous interhemispheric SST contrasts in the Atlantic (Figure 1). The AMO-related SST signals in other ocean basins are likely to play a limited role since the NASST and AMO* regressions give distinct SST patterns outside the North Atlantic (Figures 1c and 1d) but similar precipitation anomalies in the tropical Atlantic.

However, we found that the removal of GMSST from NASST is still necessary to identify the simulated AMO hydroclimate impacts in other key regions. A prominent example is rainfall over the North America, which has been widely linked to the AMO [e.g., *Enfield et al*., 2001; *McCabe et al*., 2004; *Sutton and Hodson*, 2005; *Knight et al*., 2006]. When the AMO is in its positive phase, the observations show the United States receives less than normal rainfall in both winter (Figures 3a and 3b) and summer (Figures 3e and 3f) despite different regional emphasis. Similar to the previous analyses of climate models [*Ting et al*., 2011; *Kavvada et al*., 2013; *Ruiz-Barradas et al*., 2013; *Han et al*., 2016], regressions onto the NASST in CMIP5 simulations show very weak precipitation anomalies over the United States (Figures 3c and 3g). In contrast, regressions onto the AMO* give consistent droughts over the United States across a majority of the models (Figures 3d and 3h). Given that regressions onto the NASST and AMO* produce similar AMO SST structures but distinct SST patterns outside the North Atlantic (Figures 1c and 1d), the contrasting precipitation regression values highlight the important role of AMO-related SST anomalies outside the North Atlantic in forcing precipitation anomalies over the United States. *McCabe et al*. [2004] suggested that the observed droughts over the United States are related to both the North Atlantic warming and the northeastern and tropical Pacific cooling, with the latter being captured by the AMO* (Figure 1d). The tropical Pacific warming shown in the NASST regressions (Figure 1c), which is related to Pacific climate processes rather than the AMO (Figure 2b), may force wet conditions over the United States that mask the AMO impacts. Our finding may partly explain why atmospheric general circulation models forced with prescribed AMO SST anomalies confined to the North Atlantic have difficulty simulating the United States rainfall response to the AMO [*Hodson et al*., 2010], since the La Niña-like Pacific SST anomalies during the positive AMO phase (Figure 1) could reinforce the AMO direct impacts.

Kushnir et al. [2010] found that a warmer tropical Atlantic is accompanied by the suppressed convection over the equatorial Pacific, which could excite extratropical wave responses that result in reduced rainfall over the United States. Considering the importance of the tropical Pacific forcing, we also examined the AMO-related precipitation anomalies over the tropical Pacific. Regressions onto the NASST show increased rainfall over the equatorial Pacific corresponding to the NASST-projected tropical Pacific warming (Figure 1c). On the contrary, regressions onto the AMO* show suppressed rainfall over the central equatorial Pacific, which is consistent with the results from coupled model experiments forced by AMO SST anomalies in the North Atlantic [*Dong et al*., 2006; *Lyu et al*., 2017; *Ruprich-Robert et al*., 2017]. The AMO* regressions in the CMIP5 simulations also reproduce the observed positive rainfall anomalies over the Maritime Continent during the positive AMO phase, which cannot be seen in the NASST regressions. A southward displacement of the South Pacific Convergence Zone seen in the AMO* regressions leads to increased rainfall over the east coast of Australia during DJF (Figure 3d). The increased Siberian warm season (JJA) rainfall during the positive AMO phase, as reported by *Sun et al*. [2015], cannot be seen in the CMIP5 simulations regardless of the index used for regression (Figures 3e–3h), even when the external forcings are included (supporting information Figure S5).

Another outstanding example illustrating the necessity of factoring out the global signal is the Indian summer rainfall. When the AMO is in its positive phase, the observations show more rainfall over the India during JJA (Figures 3e and 3f), indicating a stronger Indian summer monsoon [*Goswami et al*., 2006], as also confirmed in coupled model experiments [*Zhang and Delworth*, 2005, 2006; *Ruprich-Robert et al*., 2017]. Regressions onto the NASST in the CMIP5 simulations instead show inconsistent or even opposite-signed rainfall anomalies over the India (Figure 3g), while regressions onto the AMO* reveal that the CMIP5 models generally simulate increased Indian summer rainfall during the positive AMO phase as in observations (Figure 3h). Our results highlight the potential role for concurrent SST anomalies outside the North Atlantic in connecting the AMO with the Indian summer monsoon.

4. Summary and Discussion

This study aims to determine to what degree current state-of-the-art CMIP5 models can simulate the AMO-related climate signals across the globe. When the NASST is used to represent the AMO as in previous studies, the CMIP5 models mainly simulate the AMO-like SST pattern in the North Atlantic along with the associated rainfall anomalies over the Central and South America and the Sahel region as direct responses to a meridional shift of the Atlantic ITCZ. In contrast, by simply removing the GMSST from the NASST and thus separating the AMO signal with local origins in the North Atlantic from the global signal, we found that the CMIP5 models can also reproduce the observed SST anomalies outside the North Atlantic as well as hydroclimate impacts in some key regions, such as drying over the United States, wetting over the Maritime Continent and the enhanced Indian summer monsoon during the positive phase of the AMO. Our results suggest that previous analyses of climate model simulations based on the NASST only, which failed to account for the global signal, underestimated the model performance in simulating the AMO-related worldwide climate impacts. However, it should be recognized that both the observational and intermodel uncertainties are still considerably large and the multimodel ensemble mean tends to underestimate the AMO-related climate signals (supporting information Figure S8). We also found that the CMIP5 models have difficulty in reproducing some observed AMO-related regional impacts, such as its downstream effects on the Siberian warm season rainfall. Future investigations are needed to diagnose these model deficiencies.

Our results concur with *Marini and Frankignoul* [2014] who also emphasized that the global signal should be carefully removed when examining low-frequency interbasin connections. We also removed regression onto the low-pass-filtered GMSST from the NASST and found nearly identical AMO patterns, which suggests that the GMSST itself could represent local expressions of the global signal in the North Atlantic. Removing the influences of Pacific low-frequency variability on the NASST by subtracting the regression onto the low-pass-filtered TPSST of the NASST also produces similar results (supporting information Figures S9 and S10). Further intercomparisons are required to determine which approach for isolating the AMO signal is optimal [*Marini and Frankignoul*, 2014].

The agreement between observations and the CMIP5 long preindustrial simulations confirms the robust climate impacts of an AMO that is internally generated within the climate system, a conclusion that cannot be firmly drawn from analyses of the short instrumental record. Our finding that global climate models reproduce the observed major AMO climate impacts also implies that the predictability of the AMO itself [e.g., *Keenlyside et al*., 2008] may be extended to a range of regional decadal climate predictions.

Acknowledgments
We thank two anonymous reviewers for their constructive comments. This research was supported by the National Science Foundation grant AGS-1505145. The CRU TS 3.23 data were obtained from the Centre for Environmental Data Analysis (http://www.ceda.ac.uk/). The HadISST data are from the UK Met Office (http://www.metoffice.gov.uk/hadobs/hadisst/). We acknowledge the climate modeling groups (listed in the supporting information Table S1), the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM), and the Global Organization for Earth System Science Portals (GO-ESSP) for producing, coordinating, and making available the CMIP5 model output.

References

Barcikowska, M., T. Knutson, and R. Zhang (2017), Observed and simulated fingerprints of multidecadal climate variability, and their contributions to periods of global SST stagnation, *J. Clim.*, *30*, 721–737, doi:10.1175/JCLI-D-16-0443.1.

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

Chen, X., and K.-K. Tung (2014), Varying planetary heat sink led to global-warming slowdown and acceleration, *Science*, *345*(6199), 897–903, doi:10.1126/science.1254937.

Chylek, P., J. D. Klett, G. Lesins, M. K. Dubey, and N. Hengartner (2014), The Atlantic Multidecadal Oscillation as a dominant factor of oceanic influence on climate, *Geophys. Res. Lett.*, *41*, 1689–1697, doi:10.1002/2014GL059274.

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

DelSole, T., M. K. Tippett, and J. Shukla (2011), A significant component of unforced multidecadal variability in the recent acceleration of global warming, *J. Clim.*, *24*, 909–926, doi:10.1175/2010JCLI3659.1.

Delworth, T., S. Manabe, and R. Stouffer (1993), Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, *J. Clim.*, *6*(11), 1993–2011.

Delworth, T. L., and M. E. Mann (2000), Observed and simulated multidecadal variability in the Northern Hemisphere, *Clim. Dyn.*, *16*(9), 661–676, doi:10.1007/s003820000075.

Deser, C., M. A. Alexander, S.-P. Xie, and A. S. Phillips (2010), Sea surface temperature variability: Patterns and mechanisms, *Annu. Rev. Mar. Sci.*, *2*, 115–143, doi:10.1146/annurev-marine-120408-151453.

Dong, B., R. T. Sutton, and A. A. Scaife (2006), Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures, *Geophys. Res. Lett.*, *33*, L08705, doi:10.1029/2006GL025766.

England, M. H., S. McGregor, P. Spence, G. A. Meehl, A. Timmermann, W. Cai, A. S. Gupta, M. J. McPhaden, A. Purich, and A. Santoso (2014), Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus, *Nat. Clim. Chang.*, *4*(3), 222–227, doi:10.1038/nclimate2106.

Enfield, D. B., and L. Cid-Serrano (2010), Secular and multidecadal warmings in the North Atlantic and their relationships with major hurricane activity, *Int. J. Climatol.*, *30*, 174–184, doi:10.1002/joc.1881.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble (2001), The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S, *Geophys. Res. Lett.*, *28*(10), 2077–2080, doi:10.1029/2000GL012745.

Folland, C. K., T. N. Palmer, and D. E. Parker (1986), Sahel rainfall and worldwide sea temperatures, 1901–85, *Nature*, *320*, 602–607, doi:10.1038/320602a0.

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

Goswami, B. N., M. S. Madhusoodanan, C. P. Neema, and D. Sengupta (2006), A physical mechanism for North Atlantic SST influence on the Indian summer monsoon, *Geophys. Res. Lett.*, *33*, L02706, doi:10.1029/2005GL024803.

Han, Z., F. Luo, S. Li, Y. Gao, T. Furevik, and L. Svendsen (2016), Simulation by CMIP5 models of the Atlantic Multidecadal Oscillation and its climate impacts, *Adv. Atmos. Sci.*, *33*(12), 1329–1342, doi:10.1007/s00376-016-5270-4.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister (2014), Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 dataset, *Int. J. Climatol.*, *34*, 623–642, doi:10.1002/joc.3711.

Hodson, D. L. R., R. T. Sutton, C. Cassou, N. Keenlyside, Y. Okumura, and T. Zhou (2010), Climate impacts of recent multidecadal changes in Atlantic Ocean sea surface temperature: A multimodel comparison, *Clim. Dyn.*, *34*, 1041–1058, doi:10.1007/s00382-009-0571-2.

Kang, I., H. No, and F. Kucharski (2014), ENSO amplitude modulation associated with the mean SST changes in the tropical central Pacific induced by Atlantic Multidecadal Oscillation, *J. Clim.*, *27*, 7911–7920, doi:10.1175/JCLI-D-14-00018.1.

Kavvada, A., A. Ruiz-Barradas, and S. Nigam (2013), AMO's structure and climate footprint in observations and IPCC AR5 climate simulations, *Clim. Dyn.*, *41*, 1345–1364, doi:10.1007/s00382-013-1712-1.

Keenlyside, N. S., M. Latif, J. Jungclaus, L. Kornblueh, and E. Roeckner (2008), Advancing decadal-scale climate prediction in the North Atlantic sector, *Nature*, *453*, 84–88, doi:10.1038/nature06921.

Keenlyside, N. S., J. Ba, J. Mecking, N.-E. Omrani, M. Latif, R. Zhang, and R. Msadek (2015), North Atlantic multi-decadal variability—Mechanisms and predictability, in *Climate Change Multidecadal Beyond*, edited by C.-P. Chang et al., pp. 141–158, World Sci., Singapore.

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

Knight, J. R. (2009), The Atlantic Multidecadal Oscillation inferred from the forced climate response in coupled general circulation models, *J. Clim.*, *22*, 1610–1625, doi:10.1175/2008JCLI2628.1.

Knight, J. R., R. J. Allan, C. K. Folland, M. Vellinga, and M. E. Mann (2005), A signature of persistent natural thermohaline circulation cycles in observed climate, *Geophys. Res. Lett.*, *32*, L20708, doi:10.1029/2005GL024233.

Knight, J. R., C. K. Folland, and A. A. Scaife (2006), Climate impacts of the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *33*, L17706, doi:10.1029/2006GL026242.

Kosaka, Y., and S.-P. Xie (2013), Recent global-warming hiatus tied to equatorial Pacific surface cooling, *Nature*, *501*(7467), 403–407, doi:10.1038/nature12534.

Kucharski, F., F. Ikram, F. Molteni, R. Farneti, I.-S. Kang, H.-H. No, M. P. King, G. Giuliani, and K. Mogensen (2016), Atlantic forcing of Pacific decadal variability, *Clim. Dyn.*, *46*, 2337–2351, doi:10.1007/s00382-015-2705-z.

Kushnir, Y., R. Seager, M. Ting, N. Naik, and J. Nakamura (2010), Mechanisms of tropical Atlantic SST influence on North American precipitation variability, *J. Clim.*, *23*, 5610–5628, doi:10.1175/2010JCLI3172.1.

Li, X. C., D. M. Holland, E. P. Gerber, and C. Yoo (2014), Impacts of the north and tropical Atlantic Ocean on the Antarctic Peninsula and sea ice, *Nature*, *505*(7484), 538–542, doi:10.1038/nature12945.

Li, X., S.-P. Xie, S. T. Gille, and C. Yoo (2015), Atlantic-induced pan-tropical climate change over the past three decades, *Nat. Clim. Chang.*, *6*, 275–279, doi:10.1038/NCLIMATE2840.

Lyu, K., X. Zhang, J. A. Church, and J. Hu (2015), Quantifying internally generated and externally forced climate signals at regional scales in CMIP5 models, *Geophys. Res. Lett.*, *42*, 9394–9403, doi:10.1002/2015GL065508.

Lyu, K., X. Zhang, J. A. Church, and J. Hu (2016), Evaluation of the interdecadal variability of sea surface temperature and sea level in the Pacific in CMIP3 and CMIP5 models, *Int. J. Climatol.*, *36*, 3723–3740, doi:10.1002/joc.4587.

Lyu, K., J.-Y. Yu, and H. Paek (2017), The influences of the Atlantic Multidecadal Oscillation on the mean strength of the North Pacific subtropical high during boreal winter, *J. Clim.*, *30*, 411–426, doi:10.1175/JCLI-D-16-0525.1.

Maher, N., A. S. Gupta, and M. H. England (2014), Drivers of decadal hiatus periods in the 20th and 21st centuries, *Geophys. Res. Lett.*, *41*, 5978–5986, doi:10.1002/2014GL060527.

Marini, C., and C. Frankignoul (2014), An attempt to deconstruct the Atlantic Multidecadal Oscillation, *Clim. Dyn.*, *43*, 607–625, doi:10.1007/s00382-013-1852-3.

Martin, E. R., C. Thorncroft, and B. B. B. Booth (2014), The multidecadal Atlantic SST—Sahel rainfall teleconnection in CMIP5 simulations, *J. Clim.*, *27*, 784–806, doi:10.1175/JCLI-D-13-00242.1.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U.S.A.*, *101*(12), 4136–4141, doi:10.1073/pnas.0306738101.

McGregor, S., A. Timmermann, M. F. Stuecker, M. H. England, M. Merrifield, F.-F. Jin, and Y. Chikamoto (2014), Recent Walker circulation strengthening and Pacific cooling amplified by Atlantic warming, *Nat. Clim. Chang.*, *4*(10), 888–892, doi:10.1038/nclimate2330.

Mohino, E., S. Janicot, and J. Bader (2011), Sahel rainfall and decadal to multidecadal sea surface temperature variability, *Clim. Dyn.*, *37*(3), 419–440, doi:10.1007/s00382-010-0867-2.

O'Reilly, C. H., M. Huber, T. Woollings, and L. Zanna (2016), The signature of low-frequency oceanic forcing in the Atlantic Multidecadal Oscillation, *Geophys. Res. Lett.*, *43*, 2810–2818, doi:10.1002/2016GL067925.

Otterå, O. H., M. Bentsen, H. Drange, and L. Suo (2010), External forcing as a metronome for Atlantic multidecadal variability, *Nat. Geosci.*, *3*(10), 688–694, doi:10.1038/ngeo955.

Peings, Y., G. Simpkins, and G. Magnusdottir (2016), Multidecadal fluctuations of the North Atlantic Ocean and feedback on the winter climate in CMIP5 control simulations, *J. Geophys. Res. Atmos.*, *121*, 2571–2592, doi:10.1002/2015JD024107.

Qian, C., J.-Y. Yu, and G. Chen (2014), Decadal summer drought frequency in China: The increasing influence of the Atlantic Multi-decadal Oscillation, *Environ. Res. Lett.*, *9*(12), 124004, doi:10.1088/1748-9326/9/12/124004.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Ruprich-Robert, Y., R. Msadek, F. Castruccio, S. Yeager, T. Delworth, and G. Danabasoglu (2017), Assessing the climate impacts of the observed Atlantic multidecadal variability using the GFDL CM2.1 and NCAR CESM1 global coupled models, *J. Clim.*, *30*, 2785–2810, doi:10.1175/JCLI-D-16-0127.1.

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

Schlesinger, M. E., and N. Ramankutty (1994), An oscillation in the global climate system of period 65–70 years, *Nature*, *367*(6465), 723–726, doi:10.1038/367723a0.

Seager, R., N. Naik, W. Baethgen, A. Robertson, Y. Kushnir, J. Nakamura, and S. Jurburg (2010), Tropical oceanic causes of interannual to multidecadal variability in southeast South America over the past century, *J. Clim.*, *23*, 5517–5539, doi:10.1175/2010JCLI3578.1.

Shanahan, T. M., J. T. Overpeck, K. J. Anchukaitis, J. W. Beck, J. E. Cole, D. L. Dettman, J. A. Peck, C. A. Scholz, and J. W. King (2009), Atlantic forcing of persistent drought in West Africa, *Science*, *324*(5925), 377–380, doi:10.1126/science.1166352.

Song, Y., Y. Yu, and P. Lin (2014), The hiatus and accelerated warming decades in CMIP5 simulations, *Adv. Atmos. Sci.*, *31*(6), 1316–1330, doi:10.1007/s00376-014-3265-6.

Sun, C., J. Li, and S. Zhao (2015), Remote influence of Atlantic multidecadal variability on Siberian warm season precipitation, *Sci. Rep.*, doi:10.1038/srep16853.

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

Sutton, R., E. Suckling, and E. Hawkins (2015), What does global mean temperature tell us about local climate?, *Phil. Trans. R. Soc. A*, *373*, 20140426, doi:10.1098/rsta.2014.0426.

Terray, L. (2012), Evidence for multiple drivers of North Atlantic multidecadal climate variability, *Geophys. Res. Lett.*, *39*, L19712, doi:10.1029/2012GL053046.

Timmermann, A., et al. (2007), The influence of a weakening of the Atlantic meridional overturning circulation on ENSO, *J. Clim.*, *20*(19), 4899–4919, doi:10.1175/JCLI4283.1.

Ting, M., Y. Kushnir, R. Seager, and C. Li (2009), Forced and internal twentieth-century SST trends in the North Atlantic, *J. Clim.*, *22*(6), 1469–1481, doi:10.1175/2008JCLI2561.1.

Ting, M., Y. Kushnir, R. Seager, and C. Li (2011), Robust features of Atlantic multi-decadal variability and its climate impacts, *Geophys. Res. Lett.*, *38*, L17705, doi:10.1029/2011GL048712.

Ting, M., Y. Kushnir, R. Seager, and C. Li (2014), North Atlantic multidecadal SST oscillation: External forcing versus internal variability, *J. Mar. Syst.*, *133*, 27–38, doi:10.1016/j.jmarsys.2013.07.006.

Trenberth, K. E., and J. T. Fasullo (2013), An apparent hiatus in global warming?, *Earth's Future*, *1*(1), 19–32, doi:10.1002/2013EF000165.

Trenberth, K. E., and D. J. Shea (2006), Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, *33*, L12704, doi:10.1029/2006GL026894.

Wang, C., S. Dong, A. T. Evan, G. R. Foltz, and S. K. Lee (2012), Multidecadal covariability of North Atlantic sea surface temperature, African dust, Sahel rainfall and Atlantic hurricanes, *J. Clim.*, *25*, 5404–5415, doi:10.1175/JCLI-D-11-00413.1.

Wu, L., C. Li, C. Yang, and S. P. Xie (2008), Global teleconnections in response to a shutdown of the Atlantic meridional overturning circulation, *J. Clim.*, *21*, 3002–3019, doi:10.1175/2007JCLI1858.1.

Wu, Z., N. E. Huang, J. M. Wallace, B. V. Smoliak, and X. Chen (2011), On the time-varying trend in global-mean surface temperature, *Clim. Dyn.*, *37*, 759–773, doi:10.1007/s00382-011-1128-8.

Yu, J.-Y., P. Kao, H. Paek, H. Hsu, C. Hung, M. Lu, and S. An (2015), Linking emergence of the Central-Pacific El Niño to the Atlantic Multi-decadal Oscillation, *J. Clim.*, *28*, 651–662, doi:10.1175/JCLI-D-14-00347.1.

Zhang, L., and C. Wang (2013), Multidecadal North Atlantic sea surface temperature and Atlantic meridional overturning circulation variability in CMIP5 historical simulations, *J. Geophys. Res. Oceans*, *118*, 5772–5791, doi:10.1002/jgrc.20390.

Zhang, R., and T. L. Delworth (2005), Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation, *J. Clim.*, *18*(12), 1853–1860, doi:10.1175/JCLI3460.1.

Zhang, R., and T. L. Delworth (2006), Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, *Geophys. Res. Lett.*, *33*, L17712, doi:10.1029/2006GL026267.

Zhang, R., et al. (2013), Have aerosols caused the observed Atlantic multidecadal variability?, *J. Atmos. Sci.*, *70*(4), 1135–1144, doi:10.1175/JAS-D-12-0331.1.

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

Zhou, J., and K. Tung (2013), Deducing multidecadal anthropogenic global warming trends using multiple regression analysis, *J. Atmos. Sci.*, *70*, 3–8, doi:10.1175/JAS-D-12-0208.1.