Atlantic Meridional Overturning Circulation reconstructions and instrumentally observed multidecadal climate variability: A comparison of indicators

Cheng Sun1 | Jing Zhang1 | Xiang Li2 | Chunming Shi1 | Zhanqiu Gong1 | Ruiqiang Ding3 | Fei Xie1 | Panxing Lou4

1College of Global Change and Earth System Science (GCESS), Beijing Normal University, Beijing, 100875, China
2Key Laboratory of Marine Hazards Forecasting, National Marine Environmental Forecasting Center, Ministry of Natural Resources, Beijing, 100081, China
3State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, 100875, China
4Meteorological Institute of Shaanxi Province, Xi’an, 710014, China

Correspondence
Jing Zhang, College of Global Change and Earth System Science (GCESS), Beijing Normal University, Beijing 100875, China. Email: jing_zhang@mail.bnu.edu.cn

Xiang Li, Key Laboratory of Marine Hazards Forecasting, National Marine Environmental Forecasting Center, Ministry of Natural Resources, Beijing 100081, China. Email: lixiang@nmefc.cn

Funding information
National Key R&D Program of China, Grant/Award Number: 2019YFC1408004; National Natural Science Foundation of China, Grant/Award Numbers: 41775038, 41790474, 41975082; National Program on Global Change and Air-Sea Interaction, Grant/Award Numbers: GASI-IPOVAI-06, GASI-IPOVAI-03; Key Laboratory of Marine Hazards Forecasting of Ministry of Natural Resources, Grant/Award Number: LOMFI1801

Abstract
The Atlantic Meridional Overturning Circulation (AMOC) has an important role in the Earth’s climate system, but it remains unclear how the instrumentally observed multidecadal variability of the Earth’s climate is related to the AMOC. We carried out a comprehensive evaluation of five representative indicators of the AMOC, including one atmospheric index based on the effect of accumulated atmospheric forcing on the AMOC and four oceanographic indices using surface and subsurface oceanographic variables in the North Atlantic Ocean. We compared reconstructions of the AMOC against measurement records and analysed the relationships with the multidecadal variability of the annual mean surface air temperature anomalies over the North Atlantic, Northern Hemisphere and South Atlantic. All the AMOC indicators show a weakening trend during the most recent decade, which is in good agreement with the RAPID measurement record of the AMOC. Besides, the atmospheric reconstruction shows the best agreement with the observed low-frequency variation in the AMOC since 2004. The multidecadal variability in hemispheric/regional surface temperatures is closely related to all the AMOC reconstructions and opposite relationships are observed between the North Atlantic and South Atlantic oceans. The multidecadal surface air temperature anomalies associated with the variations in the AMOC are most pronounced for the atmospheric reconstruction index, which leads the variations in the surface air temperature by 4–5 years. Among the oceanographic indicators, the reconstructions using subsurface oceanographic variables performed best in terms of the relationship with the variations in the multidecadal surface air temperature.

KEYWORDS
climate, multidecadal variability, AMOC indicators

© 2020 The Authors. International Journal of Climatology published by John Wiley & Sons Ltd on behalf of the Royal Meteorological Society.
1 INTRODUCTION

It is well known that the Atlantic Meridional Overturning Circulation (AMOC) has an important role in the Earth’s climate system, redistributing oceanic heat, regulating the global energy balance and exerting significant influences on both the regional and global climate (Trenberth and Caron, 2001; Srokosz et al., 2012; Buckley and Marshall, 2016; Cherchi, 2019). The AMOC consists of an upper layer of northward-flowing warm, salty seawater, which transports heat from the Tropics and South Atlantic toward the North Atlantic, and a deeper layer of southward-flowing seawater returning the cold North Atlantic Deep Water. The AMOC therefore connects the two hemispheres and is a primary cause of interhemispheric asymmetries in surface temperature, precipitation and atmospheric energy (Buckley and Marshall, 2016) and determines the mean position of the Intertropical Convergence Zone (ITCZ) (Frierson et al., 2013). In the context of global warming, the dominant role of the AMOC may have changed from transporting oceanic heat to storing anthropogenic heat, which buffers surface warming of the planet (Chen and Tung, 2018). Nevertheless, the role of AMOC in the observed variations of global mean surface temperature remains controversial (Caesar et al., 2020). The presence of the AMOC is important for the regional climate over the continents surrounding the high-latitude North Atlantic Ocean and the heat released from the ocean to the atmosphere leads to milder winters in Europe than at similar latitudes elsewhere in the world (Palter, 2015; Yamamoto et al., 2015).

According to paleoclimate records, the AMOC has been responsible for abrupt changes in the Earth’s climate during the last glacial period (Rooth, 1982; Broecker et al., 1985; Lynch-Stieglitz, 2017). Weakening of the AMOC can lead to less heat being released to the atmosphere in the North Atlantic and the expansion of ice caps, which has been linked to the equatorward shift of the ITCZ during the Heinrich event and the Younger Dryas cold event. By contrast, a stronger AMOC can cause a warmer Arctic, less ice and a northward shift of the ITCZ (Broecker, 1994; Manighetti and McCave, 1995; Chiang and Bitz, 2005). Recent studies have shown that a decrease (increase) in the frequency of major Atlantic hurricanes is associated with a weakening (enhancement) of the AMOC (Goldenberg et al., 2001; Yan et al., 2017) and variations in the AMOC contribute to changes in monsoon rainfall in Africa and India and climate change in North America and Western Europe (Vellinga and Wood, 2002; Sutton and Hodson, 2005).

Instrumental records over the past 100 years have shown that Earth’s surface temperature is warming, but there are clear multidecadal periods with an acceleration or slowdown of warming superimposed on the centurial warming trend (Li et al., 2018). The multidecadal changes in the rate of global warming are closely related to the variability of the temperature and heat content of the oceans (Yao et al., 2017; Hu et al., 2018). The Atlantic is one of the regions with the strongest and most complex climate variability and the Atlantic Multidecadal Variability (AMV), representing the warming/cooling of the sea surface temperature (SST) in the North Atlantic, is one of the most important internal climate modes occurring in the North Atlantic (Delworth et al., 2007). The AMV plays an important role in the multidecadal variability of the temperature in the Northern Hemisphere (Levine et al., 2017; Wu et al., 2011). It exerts a significant impact not only on the regions surrounding the North Atlantic, but also extends to the Eurasian continent and East Asia (Sutton and Hodson, 2005; Lu et al., 2006; Sun et al., 2017b; 2015c). Although the Pacific decadal oscillation is known as a large driver of climate variability over North Pacific and surrounding regions (Newman et al., 2016), the AMV also plays an important part in the multidecadal variability in the Pacific and Indian oceans through atmospheric bridge and coupled oceanic–atmospheric bridge mechanisms (Zhang and Delworth, 2007; Sun et al., 2015b; 2017a; 2017b; 2019; Li et al., 2016; 2019; O’Reilly et al., 2017; Gong et al., 2019), leading to tight connections among the major ocean basins in the Tropics on multidecadal timescales.

Previous modelling studies have suggested that the low-frequency variability of the AMOC can explain the AMV by affecting the northward transport of oceanic heat (Delworth and Mann, 2000; Wang and Zhang, 2013; Zhang and Wang, 2013; Drews and Greatbatch, 2016). For example, several studies used the CMIP5 fully coupled model simulations to investigate the relationship between the AMOC and the AMV and they found that in most of the CMIP5 models the relationship between them was characterized by a positive correlation when the AMOC leads the AMV (Wang and Zhang, 2013; Zhang and Wang, 2013; Wang et al., 2017). An intensified (weakened) AMOC causes stronger (weaker) northward transport of oceanic heat and induces the warm (cold) phase of the AMV (Wang and Zhang, 2013). The entire Northern Hemisphere surface temperature and the South Atlantic also respond strongly to multidecadal changes in the AMOC in model simulations (Latif et al., 2006; Keenlyside et al., 2008; Sun et al., 2013; 2015a), showing surface temperature anomalies of opposite signs as a result of the redistribution of heat by the AMOC (Latif et al., 2004; Lopez et al., 2016). Modelling studies therefore suggest a close relationship between the AMOC and hemispheric/regional surface temperatures on multidecadal timescales. Nevertheless, a recent study pointed...
out that the response of South Atlantic SST to AMOC variability may be model dependent (Muir and Fedorov, 2015), and more importantly, it remains unclear how the instrumentally observed multidecadal climate variability is related to variations in the AMOC.

There are no multidecadal observations of the AMOC; the (RAPID means the Rapid Climate Change Programme) RAPID/MOCHA (Meridional Overturning Circulation and Heatflux Array) mooring array has only been monitoring the AMOC since 2004. However, several indicators of the strength of the AMOC have been proposed based on its physical relationship with the accumulated atmospheric forcing (Li et al., 2013; McCarthy et al., 2015; Mecking et al., 2015; Sun et al., 2015c; Delworth et al., 2016) and surface and subsurface oceanic variables (e. g., the ocean temperature and salinity) (Zhang, 2008; Yan et al., 2017; Caesar et al., 2018; Chen and Tung, 2018). These indices have been used to reconstruct the multidecadal variations of the AMOC during the past century and these reconstructions have been validated using simulations based on fully coupled ocean–atmosphere models (Zhang et al., 2013; Yan et al., 2017; O’Reilly et al., 2019). As yet, no study has compared the similarities and differences in the decadal variations in the AMOC among these reconstructions and the available measurement records. It is still unknown how much of the variance of the observed global multidecadal climate variability can be explained by the AMOC indices and a comprehensive evaluation of these reconstructions is required to address this question and to quantify the uncertainties in the multidecadal variability of the AMOC and its relationship with the global climate. These could help us further deepen our understanding of the decadal to multidecadal changes in the AMOC over the last 100 years and the impact of the AMOC on the variability of the regional and global climate. This paper aims to answer these questions through comprehensive comparisons and evaluations of several representative AMOC indicators.

2 | DATA AND METHODOLOGY

The indices evaluated differ mainly in their method of definition, selection of climate data and sources of data. We review here some of the commonly used AMOC indicators that were compared in this study.

2.1 | AMOC_SST index

Rahmstorf et al. (2015) argued that the subpolar gyre is the region most sensitive to changes in the AMOC. To remove the effect of variations in the AMOC from other large-scale changes in climate, they proposed an index for long-term variations in the AMOC based on the mean surface temperature of the subpolar gyre minus the mean SST in the Northern Hemisphere. Based on this work, Caesar et al. (2018) later developed an AMOC index that uses the mean surface temperature of the subpolar gyre region (50°–60°N, 50°–15°W) relative to the global mean SST.

This index is defined from 1871 to 2018 as the mean SST in the subpolar gyre region for the following November to May minus the global mean SST for those months (Caesar et al., 2018):

\[
\text{AMOC}_{\text{SST}} = \bar{\text{SST}}_{\text{sg}} - \text{SST}_{\text{global}}.
\]

Caesar et al. (2018) suggested that the multidecadal variability of this AMOC_SST index could be obtained by removing the long-term trend. We therefore detrended and normalized this index to give a better comparison with other indices at multidecadal timescales.

Latif et al. (2006) used an Atlantic dipole index to indicate the strength of AMOC, and the dipole index is defined as the difference in annual mean SSTs over the subpolar regions of North and South Atlantic. The SST-based AMOC indicator (AMOC_SST) from Caesar et al. (2018) covers a similar region to the Northern Pole of the dipole index according to the definitions, and the multidecadal variations of the AMOC_SST and the dipole index are quite similar (not shown here). Considering that the AMOC_SST and the dipole index are both derived from the SST data and the similarity in the variation between the two indices, we choose to use the AMOC_SST index in the study.

2.2 | AMOC_SUBT_{400} index

This index (Zhang, 2008; Yan et al., 2017) is obtained from the leading mode of the observed detrended subsurface ocean temperature anomalies at 400 m in the extratropical North Atlantic (80°W–0°, 20°–65°N) from 1955 to 2015. The northern subsurface temperature index can indicate the variation in the AMOC and changes in the subsurface ocean temperature may correspond to shifts in the location of the Gulf Stream and a slowdown in the circulation of the subpolar gyre. The shifts in the subsurface temperature are therefore directly related to the dynamics of ocean circulation.

2.3 | AMOC_SALI and AMOC_SALE indices

The subpolar upper ocean salinity index (Chen and Tung, 2018) is defined as the mean salinity from 45° to
65°N in the Atlantic basin integrated over 0–1,500 m depth. AMOC transports saline surface water from the subtropical to the subpolar Atlantic, and when AMOC is stronger (weaker), more (less) of the saline water is found in the subpolar Atlantic. This relationship suggests that the subpolar Atlantic salinity can be used as an indicator of the AMOC strength. The AMOC_SAL index from 1946 to 2015 is based on ISHII and Scripps data, whereas the AMOC_SAL index from 1946 to 2016 is obtained from EN4 data (version 4.2.1). Because the timescale of the other indices is annual, the two indices are obtained from the 12-month mean.

2.4 AMOC_NAO index

Previous modelling studies have suggested an important forcing role of the North Atlantic Oscillation (NAO) in the multidecadal variability of the AMOC (Eden and Jung, 2001; Sun et al., 2018a, 2015c; Delworth et al., 2016; O'Reilly et al., 2016). The ocean integrates the atmospheric forcing of the NAO as a result of the large inertia and responds by causing changes in the ocean circulation with a time lag of about one decade (Li et al., 2013; Gulev and Latif, 2015; Sun et al., 2015b). A time-integrated NAO index, which corresponds to the accumulated effect of NAO forcing on the Atlantic Ocean circulation, can therefore represent the multidecadal variations in the strength of the AMOC (Mecking et al., 2014; 2015; McCarthy et al., 2015; Sun et al., 2019):

\[ \int_{t_0}^{t} \text{NAO}(t) \, dt, \]

where \( t_0 \) corresponds to the initial year and \( t \) represents the number of years after the initial year. For the AMOC_NAO, \( t_0 \) corresponds to the starting year 1900 and \( t \) represents the years after 1900. This equation is similar to that used in previous studies (McCarthy et al., 2015; Sun et al., 2015b; O'Reilly et al., 2016) to construct the observational indicators of the variation in the AMOC during the twentieth century and is referred to hereafter as the AMOC_NAO index.

2.5 Comparison of indices

The reconstructions of the multidecadal variations in the AMOC can be divided into two categories based on the different physical relationships between the AMOC and the different variables: (a) atmospheric reconstructions based on the accumulated forcing role of the atmospheric circulation (AMOC_NAO); and (b) oceanographic reconstructions, which are physically connected to the convergence of heat/salinity driven by changes in the ocean circulation (Zhang, 2008; Zhang et al., 2019) and are specifically based on the relationships between the AMOC and surface and subsurface oceanographic variables (AMOC_SST, AMOC_SAL, AMOC_SAL and AMOC_SUBT). In addition, we assess the observational uncertainty in the indicators by using different available datasets of SST, ocean temperature and sea level pressure (see Supplementary Information for details, Figures S1 and S2) and find that uncertainty of the AMOC indicators due to different datasets is negligible for the multidecadal variability.

2.6 Datasets

The datasets used in this work include the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis from 1880 to 2018 (www.esrl.noaa.gov/psd/data/gridded/data.gistemp.html), the HadCRUT4 near-surface temperature ensemble data from 1850 to 2019 (www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html), the unsmoothed AMV from the Kaplan SST V2 dataset (www.esrl.noaa.gov/psd/data/timeseries/AMO/), the NAO index (Hurrell, 1995) (https://climatedataguide.ucar.edu/sites/default/files/nao_pc_annual.txt), the RAPID AMOC at 26.5°N (www.rapid.ac.uk/rapidmoc/rapid_data/) and its low-frequency variations derived from 5-year moving averages, the HadISST data used for the AMOC_SST index (Rayner et al. 2003), and National Oceanic and Atmospheric Administration/National Oceanographic Data Committee ocean temperature product for the AMOC_SUBT index (Levitus et al., 2012).

The AMOC_SUBT index is only available from 1955 to 2015, so all the indicators are compared during the same period of 1955–2015. Because our research focuses on the decadal scale, with the exception of special notes, the air temperature data and time series from 1955 to 2015 are filtered by applying an 11-year running mean. The 11-year running mean may reduce the degrees of freedom, leading to uncertainties about the relationships in the time domain (Cane et al., 2017). Previous studies have proposed several methods to perform significance tests that take into account the reduction in the degrees of freedom, such as the Monte Carlo method (Duchez et al., 2016) and the effective number of degrees of freedom (Pyper and Peterman, 1998). We applied the two-tailed Student’s t-test using the effective number of degrees of freedom, which has been widely used in previous studies focusing on the multidecadal variability of climate (Li et al., 2013; Sun et al., 2015c; 2017b). The number of effective degrees of freedom (N_{eff}) is:
where \( N \) is the sample size and \( \rho_{XX}(j) \) and \( \rho_{YY}(j) \) are the autocorrelations of two sampled time series \( X \) and \( Y \) at a lag time \( j \). We also performed similar analyses based on the unfiltered data to show that our findings are independent of the low-pass filtering procedure (Supplementary Figures S3–S5).

To better highlight and isolate the signal of multidecadal variability, we remove the externally forced signal from the temperature data. Several methods have been proposed to separating internally natural variability, including removal of the long-term linear trend (Sutton and Hodson 2005) and removal of the regressions onto the global mean surface temperature (a commonly used measure of the externally forced signal) (Ting et al., 2009; van Oldenborgh et al., 2009). Several other studies use more sophisticated methods based on the large ensemble simulation results from climate models to identify the externally forced component of the global surface temperature (Knight, 2009; Mann et al., 2014; Kajtar et al., 2019). In this study, the long-term linear trends in the surface air temperature anomaly data are removed to isolate the variability on the decadal scale by removing the least-squares linear trend of the data from all grid points. We also include the results based on the raw data (without filtering and removing trends) in the supplementary figures (available online) to verify the reliability of the results. In addition, we further test the robustness of the main findings to different methods of removing the forced signal. The results based on removal of the regressions onto the global mean surface temperature as in van Oldenborgh et al. (2009) are qualitatively consistent with those based on removal of the long-term linear trend (see Supplementary Information for details, Figures S6–S8).

3 | RESULTS

3.1 | AMOC indicators and measurement records

Figure 1 shows the time series of the five AMOC indicators. These indicators generally show consistent multidecadal variations of the AMOC during the overlapping period since the late 1940s. The AMOC was relatively strong before the early 1960s and weakened from the 1960s to the 1990s, before strengthening again after the late 1990s. The variations in the AMOC_NAO atmospheric reconstruction show a lead time of several years relative to the other oceanographic reconstructions. Nevertheless, the reconstructed AMOC indices all show a weakening trend in the 21st century.

Table 1 shows the contemporaneous correlations among different reconstructed AMOC indices and the RAPID index based on 5-year moving averages of the time series. The correlations among the different indices are positive, indicating that the multidecadal phases of the AMOC are generally consistent in different reconstructions. The correlations among the AMOC_SST, AMOC_SUBT400, AMOC_SALI and AMOC_SALIII indices are close to each other, varying between 0.70 and 0.92. The correlations of the AMOC_NAO index with other reconstructions are relatively low (0.36–0.48), possibly due to a several year lead of its variations relative to the other indices (Figure 1). Figure 1 shows that the AMOC_NAO index has a clear lead of several years relative to the four oceanographic reconstructions. We analysed the lead–lag correlations among the five indicators from 1995 to 2015. The lead–lag correlation results show that when the AMOC_NAO index leads the other four indicators by about 6–9 years, then the maximum correlation can reach >0.8 for the AMOC_SALI, AMOC_SALIII and AMOC_SUBT400 indices and 0.66 for the AMOC_SST index.

The low-frequency weakening trend of reconstructed AMOC indices in Figure 1 is consistent with the RAPID measurement record of the AMOC that began in 2004 (Figure 2a). However, it should also be noted that, according to the statistical trend analysis of the RAPID measurement records in Figure 2a, the trend in the

**FIGURE 1** Time series of the normalized AMOC indicators for the period 1871–2018. The AMOC_SST (blue line, 1871–2018) is defined by subtracting the global mean SST for the following November to May from the mean SST in the subpolar gyre for the same months; the AMOC_SUBT400 (red line, 1955–2015) is calculated from the leading mode of the observed detrended subsurface ocean temperature anomalies at 400 m in the extratropical North Atlantic; the AMOC_SALI (green line, 1946–2015) and the AMOC_SALIII (grey line, 1946–2016) is defined as the average over 45°–65°N in the Atlantic basin and integrated over 0–1,500 m. The differences mainly lie in the data used. The AMOC_NAO (orange line, 1900–2018) is calculated by a time-integrated NAO index. See Section 2 for details.
AMOC also varied during the period of the measurement records. From 2004 to 2010 the unsmoothed RAPID index weakened by \(-0.085\) Sv yr\(^{-1}\), and from 2010 to 2016 it strengthened by \(0.023\) Sv yr\(^{-1}\). The low-frequency variations in the AMOC trend in the available RAPID measured records are reasonably captured by the AMOC_NAO index (Figure 2b). The AMOC_NAO shows weakening trends before 2010, whereas after 2010 the trend flattened and strengthened slightly.

In addition, we also explored the simultaneous correlations among the five AMOC indicators and the measured RAPID records from 2004 to 2016. The smoothed RAPID AMOC with the AMOC_NAO is 0.76, higher than those with other indicator indices (between 0.35 and 0.57), consistent with the above analysis of the trend. The high correspondence between the RAPID measurements and the AMOC_NAO was analysed further. The RAPID measurement is a true estimate of the AMOC and the AMOC_NAO index largely represents the effect of accumulated atmospheric NAO forcing on the variations in the AMOC. The AMOC_NAO index has a close relationship with the surface winds that influence the ocean circulation and this factor is clearly absent in the other oceanographic indicators. We therefore further analysed the lagged correlations between the annual surface zonal winds and the RAPID measurements (Figure S9). The lagged correlations of the RAPID measurements with the surface winds indicate that the changes in surface winds over the extratropical North Atlantic lead the AMOC variations by 1–2 years. A zonal wind index based on the surface wind pattern also shows a maximum correlation (\(>0.4\)) with the AMOC measurements when the wind index leads by 2 years (Figure S9g). This is consistent with a previous modelling study that highlighted the key role of surface wind forcing in the measured variations in the AMOC (Zhao and Johns, 2014). These results may explain why the AMOC_NAO index has a better correlation with the RAPID measurements and represents more of the available measured records of variations in the AMOC than other oceanographic indicators.

### 3.2 Link between AMOC indicators and multidecadal climate variability

In contrast with previous studies based on model simulations (see Introduction for details), we investigated the AMOC–AMV relationship using the reconstructed

| TABLE 1 | Contemporaneous correlations among different reconstructed AMOC indices (1955–2015) and the RAPID measured AMOC (2004–2015) |
|---------|--------------------------------------------------|
| AMOC_NAO | AMOC_SAL\(_I\) | AMOC_SAL\(_E\) | AMOC_SST | AMOC_SUBT\(_{400}\) |
| AMOC_NAO | 1 | 0.48* | 0.36 | 0.47* | 0.43 |
| AMOC_SAL\(_I\) | 1 | 0.92* | 0.70* | 0.91* |
| AMOC_SAL\(_E\) | 1 | 0.70* | 0.91* |
| AMOC_SST | 1 | 0.70* |
| AMOC_SUBT\(_{400}\) | 1 | 0.76* | 0.57 | 0.41 | 0.35 | 0.42 |

Note: Stars indicate correlations that are statistically significant at the 90% confidence level using the two-tailed Student’s \(t\)-test. The correlation coefficients between the RAPID AMOC and the indicators are based on 5-year moving averages of the time series in the correlation analysis.
AMOC indices and instrumentally observed AMV and evaluated the performance of different AMOC indicators in explaining the AMV. A lead–lag correlation analysis between the AMV and the AMOC was conducted (Figure 3). The simultaneous correlations of the different AMOC indices with the (11-year running) AMV on decadal timescales were consistently positive (ranging from 0.40 to 0.90 in Figure 3b), indicating that a stronger AMOC index is associated with a warm phase of the AMV, consistent with previous modelling studies. The simultaneous correlation of the AMV with the AMOC_SST index is the weakest and the correlation of the AMOC_NAO index is the strongest.

Another interesting feature is that only the AMOC_NAO index shows a leading relationship with the AMV of around 3 years, whereas the other indices show a lagged relationship of up to a few years. The AMOC_NAO index is based on dynamic atmospheric forcing on the AMOC, whereas the other indices are based on the linkage between the AMOC and the oceanic variables of SST, subsurface temperature and salinity. The lead–lag correlations therefore indicate that atmospheric forcing may have a leading role in causing multidecadal variations in the AMOC and consequently the AMV (Delworth and Mann, 2000; Sun et al., 2015b) and that the forcing effect of the AMOC on the AMV, as revealed in ocean–atmosphere coupled models (Wang and Zhang, 2013; Zhang and Wang, 2013; Wang et al., 2017), are most consistently represented by the AMOC_NAO index. By contrast, previous modelling studies have suggested that significant delayed responses of the subsurface temperature and salinity in the Atlantic Ocean can be induced by the changes in AMOC associated with the AMV (Lee and Wang, 2010; Zhang and Wang, 2013). This is consistent with the lagged correlations of the oceanic AMOC indices using temperature or salinity with the AMV, showing that these indices lag the variations in the AMV.

The differences in the AMOC–AMV correlations (Figure 3) for different AMOC indicators were investigated further. First, forcing by the NAO leads the variations in the AMOC, which further induces the AMV SST anomalies as a result of the transport of heat by the ocean—that is, the NAO leads the AMOC and the AMOC leads the AMV. This may explain the lead–lag correlation between the AMOC_NAO and the AMV indices. Second, the subsurface oceanographic indicators show significant correlations with the AMV, but lag the surface AMV by around 4 years. Previous simulations by atmosphere–ocean coupled models indicated that a stronger AMOC can lead to a strengthening of the northward advection of warmer and saltier subtropical water to the subpolar North Atlantic and overturning of the ocean leads to a downward expansion of the seawater temperature and salinity anomalies from the surface to the subsurface (Wang et al., 2010; Ba et al., 2013; Zhang and Wang, 2013; Sun et al., 2015a). Meanwhile, observational analyses have shown that subpolar North Atlantic surface salinity variations are coherent with the AMV SST signal (Friedman et al. 2017) and another study based on observations and ocean reanalysis data has shown that the subsurface temperature and salinity variations over the subpolar

**Figure 3** (a) Lead–lag correlations between raw AMV time series and the five normalized AMOC indicators during the time period 1955–2015. (b) Lead–lag correlations between the 11-year running mean AMV and the five normalized AMOC indices during the time period 1955–2015. Positive (negative) lags mean that the AMOC indicators lead (lag) the AMV. The dotted lines denote the 95% confidence levels for the correlations using the effective numbers of degrees of freedom.
North Atlantic lag the surface AMV signal by around 5 years (Ruiz-Barradas et al., 2018). The lags discussed in the previous simulation and observational studies range from 5 to 10 years, comparable to the lags found here. And these previous findings based on both modelling and observational analysis may provide explanations for the lagged relationships of the subsurface oceanographic indicators relative to the surface AMV. Third, the surface oceanographic indicator (AMOC_SST) shows a relatively lower, but still statistically significant, correlation with the AMV index than the other oceanographic variables. Although the AMOC_SST index is also based on the SST data, similar to the AMV, it is defined as the mean surface temperature of the subpolar gyre region relative to the global mean SST, whereas the AMV is defined as the mean SST over the entire North Atlantic basin. The subtraction of the SST signals outside the subpolar gyre region from the original SST data could reduce the correlations of the subpolar gyre SST with the SST anomalies over other regions. This could explain the lower correlations between the two SST-based indices. In addition, we repeated the correlation analysis for the AMOC_SST index without subtracting the global mean surface temperature from the subpolar gyre region, and the correlations become comparable to other oceanographic indicators, but still lower than the AMOC_NAO indicator (Figure S10).

From a climatology viewpoint, the AMOC transports warm seawater northward and releases heat to the atmosphere, resulting in the Northern Hemisphere being slightly warmer than the Southern Hemisphere (Feulner et al., 2013; Marshall et al., 2014). A stronger AMOC may therefore lead to warmer-than-normal Northern Hemisphere and colder-than-normal Southern Hemisphere surface temperatures, respectively (Latif et al., 2006; Keenlyside et al., 2008; Sun et al., 2013). Figure 4 shows the simultaneous correlation between the AMOC indicators and the observed global annual mean surface air temperature anomalies on decadal timescales. The correlations are positive over most of the Northern Hemisphere, whereas they are mainly negative over the Southern Hemisphere; in particular, the negative correlations are strong over the subpolar Southern Hemisphere.

We used the surface temperature anomalies data from the HadCRUT product to verify the correlation analysis (Supplementary Figures S11–S13), which was consistent with the results from the GISS data. We also analysed the correlation results based on raw surface temperature anomalies (without decadal filtering or detrending procedures prior to analysis) and the results were qualitatively similar, but weaker (Supplementary Figures S3–S5). Because the AMOC_SST index was obtained by the subtraction of the global mean SST from the subpolar gyre SST, the correlations of the global surface air temperature anomalies with the AMOC_SST index are not as significant as the other indices. Nevertheless, the spatial structures are basically similar. This suggests that the total variance of the global annual mean surface air temperature anomalies can partially be explained by the variation in the AMOC, which accounts for a large proportion of

![Figure 4](image_url)  
**Figure 4** Simultaneous correlation between the AMOC indicators (a-e) and the observed global annual mean surface air temperature anomaly based on GISS data during the time period 1955–2015. The temperature data were processed by the 11-year running mean and the long-term linear trends were removed. The dotted areas denote correlations significant above the 95% level using the effective number of degrees of freedom.
the multidecadal variability of surface air temperature, as shown in the results based on the filtered data on a decadal scale.

To further investigate the relationship between surface temperatures in the Northern Hemisphere and variations in the AMOC, we analysed the lead–lag correlation between the annual mean surface air temperature anomalies in the Northern Hemisphere and the five AMOC indicators (Figure 5a). All the indicators show a simultaneous positive relationship with the annual mean surface air temperature anomalies in the Northern Hemisphere, with the simultaneous correlations ranging from 0.5 to 0.8. This indicates that a stronger AMOC is associated with warming of the annual mean surface air temperature anomalies in the Northern Hemisphere. The AMOC_SST index showed a weaker correlation with the surface temperature in the Northern Hemisphere, probably due to the subtraction of the SST signals outside the subpolar gyre region, whereas the correlations for the other indices were similar in magnitude. With respect to the lead–lag relationship between the AMOC and the annual mean surface air temperature anomalies, there was a strong lagged relationship between the temperature anomalies in the Northern Hemisphere and the AMOC_NAO index, with the AMOC_NAO index leading by around 4 years and the correlation reaching up to 0.9.

By contrast, the lead–lag correlations for the other indices show strong peaks of positive correlations when the annual mean surface air temperature anomalies in the Northern Hemisphere lead the AMOC indicators by several years. The positive correlations were lower than the AMOC_NAO when the AMOC led the temperature anomalies.

The lead–lag correlation maps between the annual mean surface air temperature anomalies in the Northern Hemisphere and AMOC reconstructions (Figures 6 and S14) show that when the AMOC indices lead the surface air temperature (i.e., at positive lags), the AMOC_NAO index shows the highest correlation with the multidecadal variability in surface temperature, maximum at the lag about 4 years, whereas the other oceanographic indicators show lower correlations. The three oceanographic indicators (AMOC_SALI, AMOC_SALE and AMOC_SUBT400) show similar lead–lag relationships with the multidecadal variability of the Northern Hemisphere temperature in terms of phase and magnitude and it should be noted that the AMOC_SALI and AMOC_SALE indices are based on the salinity and are independent of the variations in the seawater temperature. Previous studies have suggested a strong coherence between the AMV and the multidecadal variability of the mean surface temperature in the Northern Hemisphere.
The North Atlantic region used to define the AMV index covers nearly a quarter of the hemisphere and overlapping of the regions might influence the independence of the two indices. To test whether the strong coherence between the AMV and the mean surface temperature in the Northern Hemisphere is a result of the inclusion of the North Atlantic region in the Northern Hemisphere average of the surface temperature, we repeated the lagged correlation analysis with the exclusion of the North Atlantic region ($0^\circ$–$60^\circ$N, $70^\circ$–$10^\circ$W) when calculating the mean surface temperature of the Northern Hemisphere. We first compared the time series of the AMV and the annual mean surface air temperature anomalies in the Northern Hemisphere with the North Atlantic region excluded from the average for the Northern Hemisphere (hereafter referred to as the NH–NA) during the time period 1900–2017. Figure S15 shows that there is good agreement between the NH–NA annual mean surface air temperature anomalies and that the AMV is evident on multidecadal timescales. The correlation coefficient between the two indices on a multidecadal timescale is 0.69 for the whole analysis period and reaches 0.88 for the period after 1955, both significant at the 95% confidence level. This indicates a significant influence of the AMV signal on the multidecadal variability of the surface temperature of the Northern Hemisphere outside the North Atlantic region and that the strong coherence between the AMV and the mean surface temperature of the Northern Hemisphere is unlikely to be due to the inclusion of the North Atlantic in the Northern Hemisphere mean. Moreover, the influences of AMV on surface temperature variations in the pan-Atlantic region and other remote regions/basins have been investigated in previous studies and the underlying mechanisms are mainly through atmospheric and coupled oceanic-atmospheric processes (Zhang et al. 2019 and references therein).

We also analysed the lagged correlations of the five AMOC indicators with the NH–NA mean surface temperature anomalies (Figure 5b) and there was no significant difference after the exclusion of the North Atlantic region from the Northern Hemisphere average of the surface temperature. The consistence of the lagged relationships of the AMOC indices with the AMV and NH–NA surface temperature indicates that the AMV also acts as an important intermediate between the AMOC indices and the multidecadal variability of the NH–NA mean surface temperature.

With respect to the relationship between the AMOC and multidecadal variability of the North Pacific SST, the AMOC indices all show signatures of the AMOC over the Pacific basin for both the simultaneous and lagged correlation maps (Figures 4 and 6). The connections between

(Knight et al., 2005; Li et al., 2013) and most of the multidecadal variability in the Northern Hemisphere can be explained by the AMV signal. The lagged relationships of the five AMOC indices with the temperature anomalies in the Northern Hemisphere are highly consistent with those with the AMV (Figure 3), indicating an important role of the AMV in mediating between the AMOC and the annual mean surface air temperature anomalies in the Northern Hemisphere.
AMOC indicators and multidecadal variability in the Pacific basin are stronger when the AMOC leads the North Pacific SST by several years and relatively weak for the simultaneous correlation map. Among the different indicators, the AMOC–North Pacific relationships are tighter for the subsurface oceanographic variables indices (AMOC_SUBT400, AMOC_SAL1, and AMOC_SAL2), but slightly weaker for the AMOC_NAO and AMOC_SST indices, all showing SST warming (cooling) in the mid-latitude North Pacific associated with strengthening (weakening) of the AMOC (Cai et al., 2019). Previous modelling studies have suggested that the weakening of the AMOC in a freshwater hosing experiment can induce cooling of SSTs in the North Pacific and the mechanism can be explained by oceanic and atmospheric pathways (Wu et al., 2008; Okumura et al., 2009; Wang et al., 2014). Our study provides further evidence for the AMOC–North Pacific connection using both reconstructions and observations.

Previous modelling studies have shown that a stronger AMOC corresponds to an increase in the northward transport of oceanic heat, leading to warming of the upper layer of the ocean in the North Atlantic and cooling in the South Atlantic (Keenlyside et al., 2008). This SST pattern is referred to as the bipolar seesaw or the interhemispheric SST dipole (Broecker, 1998; Latif et al., 2004; Sun et al., 2013; 2015a; 2018b). We further evaluated the relationships between the five AMOC indicators and the annual mean SST anomalies in the South Atlantic (70°W–10°E, 30°–60°S). The simultaneous relationships between the observed decadal variations in SST with the AMOC indices show consistent negative correlations over the South Atlantic basin (Figure 7), with the correlations varying modestly across different indices. The lead–lag correlations between the five AMOC indicators and the annual mean SST anomalies in the South Atlantic show that the simultaneous correlations range from −0.5 to −0.8, with the AMOC_SST index being the lowest. Similar to the situations for the AMV and the North Atlantic, only the AMOC_NAO index

**FIGURE 7** Lead–lag correlations between annual mean SST anomaly in the South Atlantic (70°W–10°E, 30°–60°S) (processed by the 11-year running mean with the long-term linear trends removed and based on GISS data) and five normalized AMOC indicators during 1955–2015. Positive (negative) lags mean that the AMOC indicators lead (lag) the South Atlantic annual mean SST anomaly. The dotted lines denote the 95% confidence levels for the correlations using the effective number of degrees of freedom.

**FIGURE 8** Correlation maps between the South Atlantic (70°W–10°E, 30°–60°S) annual mean SST anomaly (processed by the 11-year running mean with the long-term linear trends removed and based on GISS data) and the five normalized AMOC indicators (a–e) when all the AMOC indices lead the temperature anomalies by 5 years for the time period 1955–2015. The dots indicate correlations significant above the 95% level using the effective number of degrees of freedom.
shows a 5-year lead relative to the variations in the annual mean SST anomalies in the South Atlantic, while the other indices lag by several years. The lead–lag correlation maps between the annual mean SST anomalies in the South Atlantic and the AMOC indices (Figures 8 and S16) also indicate that the antiphase relationship is strongest for the AMOC_NAO index and relatively weak for other indices when the AMOC indices lead the SST anomalies by 5 years.

To further highlight and evaluate the contrasting roles of the AMOC on the surface temperature anomalies in the Northern Hemisphere and South Atlantic, the Northern Hemisphere annual mean surface air temperature anomalies and the South Atlantic annual mean SST anomalies during the 1955–2015 regressions onto the five indicators were averaged over the two basins (Figure 9). There is a clear interhemispheric temperature dipole associated with the variations in the strength of the AMOC. The AMOC_NAO index has a more significant impact on variations in temperature in the Northern Hemisphere and the South Atlantic than the other indices. Our findings therefore provide further evidence from both observations and reconstructions for an interhemispheric temperature dipole and its association with the AMOC.

**4 | DISCUSSION AND CONCLUSIONS**

The Atlantic Ocean has an important role in the control of the Earth’s climate as a result of major ocean circulation: the AMOC. The transport of heat in the ocean by the AMOC helps to maintain the mean climate state and variations in the strength of the AMOC can have significant impacts on the climate on a range of timescales. Several indicators have been reconstructed to describe the multidecadal variability of the strength of the AMOC over the past century, including both atmospheric (AMOC_NAO) and oceanographic (i.e., salinity, surface and subsurface ocean temperature) indices. We evaluated the five main indicators for the AMOC based on comparisons with the decadal observational records of the strength of the AMOC and its relationship with the regional and hemispheric climate on multidecadal timescales. The results of our evaluation show that there are both differences and common features among the five indicators.

1. All the AMOC indices are positively correlated with the strength of the AMOC measured by RAPID since 2004 (between 0.32 and 0.74), which shows a weakening trend from 2004 to 2010 and a slight recovery after 2010. But not all the AMOC indicators capture the low-frequency variability in the RAPID record fully. The AMOC_NAO reconstruction shows the highest and most significant correlation with the observations, whereas the correlations with the oceanographic reconstructions are relatively low.

2. All the AMOC indices are closely related to the AMV and the surface temperature anomalies in the Northern Hemisphere and the South Atlantic on multidecadal timescales. An opposite relationship is observed between the Northern Hemisphere and the South Atlantic. The correlation of the hemispheric and
regional surface temperature anomalies with the AMOC_NAO reconstruction is largest when the AMOC_NAO leads by up to 4–5 years. The correlations for the oceanographic variables show maxima when they lag by 4–5 years and the simultaneous correlations are slightly lower. The oceanographic reconstructions using subsurface variables (e.g., salinity and the subsurface ocean temperature) show larger correlations than the reconstructions using surface variables (e.g., the SST).

The relationships between the AMOC and hemispheric/regional surface temperature anomalies on multidecadal timescales have been studied previously using model simulations. The latest CMIP5 fully coupled models show a maximum strength of the AMOC several years before the maximum warming in the North Atlantic and Northern Hemisphere in both preindustrial and historical scenarios (Zhang and Wang, 2013; Sun et al., 2015c; 2019; Wang et al., 2017; Wills et al., 2019). The time lag of the surface temperature relative to the AMOC can be explained by the transport of oceanic heat. Our results suggest that the AMOC_NAO reconstruction best captures this modelling feature, further confirming that the AMOC has a causal role in the multidecadal variability of surface temperatures (Knight et al., 2005). The other oceanographic reconstructions using subsurface oceanic variables show a time lag relative to the surface temperature, which could be explained by the time taken by the subsurface seawater to adjust to changes in the surface temperature (Wang and Zhang, 2013).

This evaluation of the AMOC indicators gives us a deeper understanding of the changes in the AMOC and sheds light on the driving mechanism of the multidecadal variability of surface temperatures. Chen and Tung (2018) investigated the global scale response to the variations of AMOC strength by analysing the relationship between AMOC indicators and multidecadal changes in the warming rates of global mean surface temperature. Caesar et al. (2020) discussed the simultaneous correlations between the global mean surface temperature and AMOC indicators. Different from their studies, our current analysis focuses on the regional and hemispheric scales of the surface temperature variations, and our study shows that the responses of surface temperature in two hemispheres may be opposite due to the horizontal transport of heat by the AMOC. In addition, our results highlight the lead–lag relationships between the AMOC indicators and surface temperature variations which have not been investigated in the previous two studies.

One limitation of this study is that we used instrumental observations of surface temperature, which are only available for the last 100 years. O’Reilly et al. (2019) confirmed a close relationship between the AMV and AMOC_NAO before the preindustrial period in a study using several different AMV reconstructions. A further investigation into the relationships between long-term reconstructions of the AMOC and surface temperatures in the Northern Hemisphere and South Atlantic requires future work. Another limitation is that the currently available records of AMOC from the RAPID measurements are too short to fully evaluate the multidecadal AMOC variability, and future research is warranted as more measurement records accumulate. The significance test for the correlation maps in the current study takes into account the temporal autocorrelation of the data at each grid cell by introducing the effective degrees of freedom. Nevertheless, the spatial autocorrelation in the gridded data and the effect of multiple testing on the significance level of the correlation maps (Wilks 2016) warrant further examination. Our study focused on the relationships between surface temperatures and the AMOC. Previous modelling studies have also indicated an important role for the AMOC in the multidecadal variability of other climate variables (e.g., precipitation, atmospheric circulations and energy). Follow-up studies will therefore use reconstructions to examine the relationships between the AMOC and these climate quantities.

ACKNOWLEDGEMENTS
The authors wish to thank four anonymous reviewers for their constructive comments that significantly improved the quality of this paper. This work was jointly supported by the National Key R&D Program of China (2019YFC1408004), National Natural Science Foundation of China (41775038, 41975082 and 41790474), the National Program on Global Change and Air–Sea Interaction (GASI-IPOVAI-03 and GASI-IPOVAI-06), Key Laboratory of Marine Hazards Forecasting of Ministry of Natural Resources (LOMF1801).

ORCID
Cheng Sun © https://orcid.org/0000-0003-0474-7593
Fei Xie © https://orcid.org/0000-0003-2891-3883

REFERENCES
Ba, J., Keenlyside, N.S., Park, W., Latif, M., Hawkins, E. and Ding, H. (2013) A mechanism for Atlantic Multidecadal Variability in the Kiel climate model. Climate Dynamics, 41(7–8), 2133–2144.
Broecker, W.S. (1994) Massive iceberg discharges as triggers for global climate change. Nature, 372(6505), 421–424.
Broecker, W.S. (1998) Paleoocean circulation during the last deglaciation: a bipolar seesaw? *Paleoceanography*, 13(2), 119–121.
Broecker, W.S., Petet, D.M. and Rind, D. (1985) Does the ocean–atmosphere system have more than one stable mode of operation? *Nature*, 315(6014), 21.
Buckley, M.W. and Marshall, J. (2016) Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: a review. *Reviews of Geophysics*, 54(1), 5–63.
Caesar, L., Rahmstorf, S. and Feulner, G. (2020) On the relationship between Atlantic Meridional Overturning Circulation slowdown and global surface warming. *Environmental Research Letters*, 15(2), 1–8.
Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V. (2018) Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, 556(7700), 191–196.
Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.S., Yu, J.Y., Stuecker, M.F., Santoso, A., Li, X. and Ham, Y.G. (2019) Panropical climate interactions. *Science*, 363(6430), p. eaav4236.
Cane, M.A., Clement, A.C., Murphy, L.N. and Bellomo, K. (2017) Low-pass filtering, heat flux, and Atlantic Multidecadal Variability. *Journal of Climate*, 30(18), 7529–7553.
Chen, X. and Tung, K.K. (2018) Global surface warming enhanced by weak Atlantic overturning circulation. *Nature*, 559(7714), 387–391.
Cherchi, A. (2019) Connecting AMOC changes. *Nature Climate Change*, 9, 729–730.
Chiang, J.C. and Bitz, C.M. (2005) Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics*, 25(5), 477–496.
Delworth, T.L. and Mann, M.E. (2000) Observed and simulated multidecadal variability in the Northern Hemisphere. *Climate Dynamics*, 16(9), 661–676.
Delworth, T.L., Zeng, F., Vecchi, G.A., Yang, X., Zhang, L. and Zhang, R. (2016) The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere. *Nature Geoscience*, 9(7), 509–512.
Delworth, T.L., Zhang, R. and Mann, M.E. (2007) Decadal to centennial variability of the Atlantic from observations and models. In: Schmitzner, A., JCH, C. and Hemming, S.R. (Eds.) *Past and Future Changes of the Oceans Meridional Overturning Circulation: Mechanisms and Impacts*. Geophysical Monograph Series 173. Washington, DC: American Geophysical Union, pp. 131–148.
Drews, A. and Greatbatch, R.J. (2016) Atlantic Multidecadal Variability in a model with an improved North Atlantic current. *Geophysical Research Letters*, 43(15), 8199–8206.
Duchez, A., Frajka-Williams, E., Josey, S.A., Evans, D.G., Grist, J.P., Marsh, R., McCarthy, G.D., Sinha, B., Berry, D.I. and Hirschi, J. J. (2016) Drivers of exceptionally cold North Atlantic Ocean temperatures and their link to the 2015 European heat wave. *Environmental Research Letters*, 11(7), 074004.
Eden, C. and Jung, T. (2001) North Atlantic interdecadal variability: oceanic response to the North Atlantic Oscillation (1865–1997). *Journal of Climate*, 14(5), 676–691.
Feulner, G., Rahmstorf, S., Levermann, A. and Volkwardt, S. (2013) On the origin of the surface air temperature difference between the hemispheres in earth’s present-day climate. *Journal of Climate*, 26(18), 7136–7150.
Friedman, A.R., Reverdin, G., Khodri, M. and Gastineau, G. (2017) A new record of Atlantic Sea surface salinity from 1896 to 2013 reveals the signatures of climate variability and long-term trends. *Geophysical Research Letters*, 44(4), 1866–1876.
Frierson, D.M., Hwang, Y.T., Fucciar, N.S., Seager, R., Kang, S.M., Donohoe, A., Maroon, A., Liu, E. and Battisti, D.S. (2013) Contribution of ocean overturning circulation to tropical rainfall peak in the Northern Hemisphere. *Nature Geoscience*, 6(11), 940–944.
Goldenberg, S.B., Landsea, C.W., Mestas-Nuñez, A.M. and Gray, W. M. (2001) The recent increase in Atlantic hurricane activity: causes and implications. *Science*, 293(5529), 474–479.
Gong, Z., Sun, C., Li, J., Feng, J., Xie, F., Ding, R., Yang, Y. and Xue, J. (2019) An inter-basin teleconnection from the North Atlantic to the subarctic North Pacific at multidecadal time scales. *Climate Dynamics*, 54, 1–16.
Gulev, S.K. and Latif, M. (2015) Ocean science: the origins of a climate oscillation. *Nature*, 521(7553), 428–430.
Hu, Z., Hu, A. and Hu, Y. (2018) Contributions of Interdecadal Pacific oscillation and Atlantic multidecadal oscillation to Global ocean heat content distribution. *Journal of Climate*, 31(3), 1227–1244.
Hurrell, J.W. (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, 269 (5224), 676–679.
Kajtar, J.B., Collins, M., Frankcombe, L.M., England, M.H., Osborn, T.J. and Juniper, M. (2019) Global mean surface temperature response to large-scale patterns of variability in observations and CMIP5. *Geophysical Research Letters*, 46(4), 2232–2241.
Keenlyside, N.S., Latif, M., Jungclaus, J., Kornblueh, L. and Roeckner, E. (2008) Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, 453(7191), 84–88.
Knight, J.R. (2009) The Atlantic multidecadal oscillation inferred from the forced climate response in coupled general circulation models. *Journal of Climate*, 22(7), 1610–1625.
Knight, J.R., Allan, R.J., Folland, C.K., Vellinga, M. and Mann, M. E. (2005) A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophysical Research Letters*, 32(20).L20708. https://doi.org/10.1029/2005GL024233.
latif, M., Böning, C., Willebrand, J., Biastoch, A., Dengg, J., Keenlyside, N., Schweckendiek, U. and Madec, G. (2006) Is the thermohaline circulation changing? *Journal of Climate*, 19(18), 4631–4637.
latif, M., Roeckner, E., Botzet, M., Esch, M., Haak, H., Hagemann, S., Jungclaus, J., Legutke, S., Marsland, S., Mikolajewicz, U. and Mitchell, J. (2004) Reconstructing, monitoring, and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature. *Journal of Climate*, 17(7), 1605–1614.
Lee, S.K. and Wang, C. (2010) Delayed advective oscillation of the Atlantic thermohaline circulation. *Journal of Climate*, 23(5), 1254–1261.
Levine, A.F., McPhaden, M.J. and Frierson, D.M. (2017) The impact of the AMO on multidecadal ENSO variability. *Geophysical Research Letters*, 44(8), 3877–3886.
Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S. and Zweng, M.M. (2012) World Ocean heat
content and thermosteric sea level change (0–2000 m), 1955–2010. Geophysical Research Letters, 39(10), 1–5.

Li, J., Sun, C. and Jin, F.F. (2013) NAO implicated as a predictor of Northern Hemisphere mean temperature multidecadal variability. Geophysical Research Letters, 40(20), 5497–5502.

Li, J., Zheng, F., Sun, C., Feng, J. and Wang, J. (2019) Pathways of influence of the Northern Hemisphere mid-high latitudes on east Asian climate: a review. Advances in Atmospheric Sciences, 36(9), 902–921.

Li, J.P., Sun, C. and Ding, R.Q. (2018) Decadal Coupled-ocean-Atmosphere Interaction in North Atlantic and Globalwarming Hiatus. Special Publications of the International Union of Geodesy and Geophysics. UK: Cambridge University Press, pp. 131–143.

Li, X., Xie, S.P., Gille, S.T. and Yoo, C. (2016) Atlantic-induced pan-tropical climate change over the past three decades. Nature Climate Change, 6(3), 275–279.

Lopez, H., Dong, S., Lee, S.K. and Goni, G. (2016) Decadal modulations of interhemispheric global atmospheric circulations and monsoons by the South Atlantic Meridional OVERTURNING CIRCULATION. Journal of Climate, 29(5), 1831–1851.

Lu, R., Dong, B. and Ding, H. (2006) Impact of the Atlantic multidecadal oscillation on the Asian summer monsoon. Geophysical Research Letters, 33(24), L24701.

Lynch-Stieglitz, J. (2017) The Atlantic Meridional Circulation and abrupt climate change. Annual Review of Marine Science, 9, 83–104.

Manighetti, B. and McCave, I.N. (1995) Late glacial and Holocene palaeocurrents around Rockall Bank, NE Atlantic Ocean. Paleoceanography, 10(3), 611–626.

Mann, M.E., Steinman, B.A. and Miller, S.K. (2014) On forced temperature changes, internal variability, and the AMO. Geophysical Research Letters, 41(9), 3211–3219.

Marshall, J., Donohoe, A., Ferreira, D. and McGee, D. (2014) The ocean’s role in setting the mean position of the inter-tropical convergence zone. Climate Dynamics, 42(7–8), 1967–1979.

McCarthy, G.D., Haigh, I.D., Hirschi, J.J.M., Grist, J.P. and Smeed, D.A. (2015) Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. Nature, 521 (7553), 508–510.

Mecking, J.V., Keenlyside, N.S. and Greatbatch, R.J. (2014) Stochastically-forced multidecadal variability in the North Atlantic: a model study. Climate Dynamics, 43(1–2), 271–288.

Mecking, J.V., Keenlyside, N.S. and Greatbatch, R.J. (2015) Multiple timescales of stochastically forced North Atlantic Ocean variability: a model study. Ocean Dynamics, 65(9–10), 1367–1381.

Muir, L.C. and Fedorov, A.V. (2015) How the AMOC affects ocean temperatures on decadal to centennial timescales: the North Atlantic versus an interhemispheric seesaw. Climate Dynamics, 45(1–2), 151–160.

Newman, M., Alexander, M.A., Ault, T.R., Cobb, K.M., Deser, C., Di Lorenzo, E., Mantua, N.J., Miller, A.J., Minobe, S., Nakamura, H., Schneider, N., Vimont, D.J., Phillips, A.S., Scott, J.D. and Smith, C.A. (2016) The Pacific decadal oscillation, revisited. Journal of Climate, 29(12), 4399–4427.

Okumura, Y.M., Deser, C., Hu, A., Timmermann, A. and Xie, S.P. (2009) North Pacific climate response to freshwater forcing in the subarctic North Atlantic: oceanic and atmospheric pathways. Journal of Climate, 22(6), 1424–1445.

O’Reilly, C.H., Huber, M., Woollings, T. and Zanna, L. (2016) The signature of low-frequency oceanic forcing in the Atlantic multidecadal oscillation. Geophysical Research Letters, 43(6), 2810–2818.

O’Reilly, C.H., Woollings, T. and Zanna, L. (2017) The dynamical influence of the Atlantic multidecadal oscillation on continental climate. Journal of Climate, 30(18), 7213–7230.

O’Reilly, C.H., Zanna, L. and Woollings, T. (2019) Assessing external and internal sources of Atlantic Multidecadal Variability using models, proxy data, and early instrumental indices. Journal of Climate, 32(22), 7727–7745.

Palter, J.B. (2015) The role of the Gulf stream in European climate. Annual Review of Marine Science, 7, 113–137.

Pyper, B.J. and Peterman, R.M. (1998) Comparison of methods to account for autocorrelation in correlation analyses of fish data. Canadian Journal of Fisheries and Aquatic Sciences, 55(9), 2127–2140.

Rahmstorf, S., Box, J.E., Feulner, G., Mann, M.E., Robinson, A., Rutherford, S. and Schaffernicht, E.J. (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Climate Change, 5(5), 475–480.

Rayner, N.A.A., Parker, D.E., Horton, E.B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research: Atmospheres, 108(D14), 4407.

Rooth, C. (1982) Hydrology and ocean circulation. Progress in oceanography, 11(2), 131–149.

Ruiz-Barradas, A., Chafik, L., Nigam, S. and Håkkinen, S. (2018) Recent subsurface North Atlantic cooling trend in context of Atlantic decadal-to-multidecadal variability. Tellus A: Dynamic Meteorology and Oceanography, 70(1), 1–19.

Srokosz, M., Baringer, M., Bryden, H., Cunningham, S., Delworth, T., Lozier, S., Marotzke, J. and Sutton, R. (2012) Past, present, and future changes in the Atlantic Meridional Overturning Circulation. Bulletin of the American Meteorological Society, 93(11), 1663–1676.

Sun, C., Kucharski, F., Li, J., Jin, F.F. and Ding, R. (2017a) Western tropical Pacific multidecadal variability forced by the Atlantic multidecadal oscillation. Nature Communications, 8, 15998.

Sun, C., Li, J., Ding, R. and Jin, Z. (2017b) Cold season Africa-Asia multidecadal teleconnection pattern and its relation to the Atlantic Multidecadal Variability. Climate Dynamics, 48(11–12), 3903–3918.

Sun, C., Li, J., Feng, J. and Xie, F. (2015b) A decadal-scale teleconnection between the North Atlantic Oscillation and subtropical eastern Australian rainfall. Journal of Climate, 28(3), 1074–1092.

Sun, C., Li, J. and Jin, F.F. (2015a) A delayed oscillator model for the quasi-periodic multidecadal variability of the NAO. Climate Dynamics, 45(7–8), 2083–2099.

Sun, C., Li, J., Jin, F.F. and Ding, R. (2013) Sea surface temperature inter-hemispheric dipole and its relation to tropical precipitation. Environmental Research Letters, 8(4), 044006.

Sun, C., Li, J., Kucharski, F., Kang, I.S., Jin, F.F., Wang, K., Wang, C., Ding, R. and Xie, F. (2019) Recent acceleration of Arabian Sea warming induced by the Atlantic-western Pacific trans-basin multidecadal variability. Geophysical Research Letters, 46(3), 1662–1671.
SUN ET AL.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Sun C, Zhang J, Li X, et al. Atlantic Meridional Overturning Circulation reconstructions and instrumentally observed multidecadal climate variability: A comparison of indicators. Int J Climatol. 2021;41:763–778. https://doi.org/10.1002/joc.6695