Timescale-dependent AMOC–AMO relationship in an earth system model of intermediate complexity

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Abstract
The relationship between Atlantic multi-decadal oscillation (AMO) and Atlantic meridional overturning circulation (AMOC) is examined with respect to two (inter- and multi-decadal) different timescales using a long-term unforced simulation of an earth system model of intermediate complexity. In the inter-decadal timescale, the AMO and the AMOC establish a self-sustaining oscillatory mode; the AMOC induces the positive AMO through meridional heat transport (MHT), but with the time delay of approximately 7 years as the AMOC anomalies propagate southward over time within the Atlantic basin. After then, the AMO reduces the density in the main sinking region and brings the negative phase of the AMOC, which results in the rest half of the cycle. On the other hand, in the multi-decadal timescale, the AMO and the AMOC are almost in phase because the AMOC is spatially stationary, resulting in a pan-Atlantic surface warming. In addition, the Arctic-originated density fluctuations are required for the multi-decadal AMOC to switch its phase. The results obtained in this study suggest that timescale dependency should be considered when investigating the AMOC–AMO relationship.

KEYWORDS
Atlantic meridional overturning circulation, Atlantic multi-decadal oscillation, multiple timescales

1 | INTRODUCTION

Decadal to multi-decadal climate variability over the Northern Atlantic Ocean is primarily driven by two climate phenomena—AMO and AMOC. The AMO–AMOC interactions have been the subject of many recent studies, although a majority of these studies have focused on how the AMOC influences the AMO (Mantua et al., 1997; Knight et al., 2005; Zhang and Wang, 2013; Ba et al., 2014; Marino and Frankignoul, 2014; Schleussner et al., 2014; Tandon and Kushner, 2015; Zhang and Zhang, 2015; Trenary and DelSole, 2016; Zhang et al., 2019). It has been suggested that ocean-circulation anomalies associated with AMOC modify the sea surface temperature (SST) distribution of the northern Atlantic Ocean via heat redistribution, and thus, they influence the AMO. Further, the SST changes associated with the AMO modify the ocean surface density and surface winds, which then affect the efficiency of deep-water formations (e.g., Yang et al., 2016); thus, the AMO influences the AMOC.

The above-mentioned mechanism hints at the possibility of that the two phenomena form an oscillatory...
relationship; the strong AMOC would lead up to the warm AMO and the warming-induced density changes would lessen the AMOC intensity, which in turn, would result in the rest half cycle. Indeed, Zhang and Wang (2013) analysed the AMOC–AMO relationship in the Coupled Model Inter-comparison Project Phase 5 (CMIP5) and showed through lead–lag correlations that the majority (11 out of 18) of the models simulated such an oscillatory relationship. However, the detailed behaviour was quite inconsistent between the models. For example, the time lag by which the positive AMOC (AMO) anomaly leads the positive AMO (negative AMOC) differed from model to model. Whether the AMOC and AMO have a positive correlation or a negative correlation on the simultaneous relationship was also diverse. Some models that were not featured by an oscillatory relationship even simulated single-signed (either positive- or negative-only) correlations, irrespective of the lag (e.g., CCSM4, MIROC-ESM, FGOALS-g2, HadGEM2-ES, and MRI-CGCM3; see their Figure 10). Such diverse behaviours found in the CMIP5 models imply that the mechanism of the AMOC–AMO interaction may differ by the individual model, and thus our current understanding of the AMOC–AMO relationship may still be insufficient. Therefore, it is worth exploring in more detail how the AMOC and AMO interact with each other.

In the previous analysis on the lead and lag relationships between the AMO and the AMOC, it has not been considered that the two climate phenomena operate differently in different timescales. In fact, the AMO is known to have two dominant timescales, and the corresponding mechanisms differ from each other (Frankcombe et al., 2010; Lin et al., 2019). The relatively short-term variability with about 20-year period has been considered as the Atlantic-intrinsic mode featured by the westward-propagating SST anomalies of the thermal oceanic Rossby wave (Frankcombe et al., 2010). On the other hand, studies have suggested that the AMO variability longer than 50 years is primarily driven by its interaction with atmospheric variability (Eden and Jung, 2001; Lin et al., 2019), the Arctic Ocean (Belkin et al., 1998; Zhang and Vallis, 2006), or both (Frankcombe et al., 2010). For example, Belkin et al. (1998) and Zhang and Vallis (2006) demonstrated that the Arctic subsurface salinity, fluctuating with a period of 50–70 years, influences the North Atlantic climate through modulation of currents, sea ice extent, temperature, and so on. Lin et al. (2019) demonstrated that the 50–80-year variability of the AMO is associated with the tropical Pacific-originated atmospheric variability that modulates the transport of warm and saline water into the Greenland-Iceland-Norwegian (GIN) Seas. Eden and Jung (2001) reported that the low-frequency variability of the North Atlantic Oscillation (NAO) induces changes in SST via changes in the ocean circulation.

The AMOC also has two dominant timescales—inter-decadal (10–30 years) and multi-decadal (>50 years)—in model simulations (Jackson and Vellinga, 2013). Inter-decadal timescale variability is considered to be associated with atmospheric variability, such as the NAO, via the transport of heat and freshwater into the convection site of the AMOC (Eden and Willebrand, 2001; Dai et al., 2005; Dong and Sutton, 2005; Xu et al., 2019). The multi-decadal-to-centennial timescale variability is considered to be associated with the transport of salinity from the Arctic to the Atlantic convection site (Delworth et al., 1997; Jungclaus et al., 2005; Hawkins and Sutton, 2008).

Since the operation mechanisms of the AMOC and the AMO are distinct at relatively high and low frequencies, the way that they interact with each other may also vary depending on the timescale of interest; however, this dependency has not been investigated to date. Here, a 3,000-year unforced simulation, obtained from a 3D fully coupled model, is used to investigate the AMO–AMOC relationship for the inter-decadal and multi-decadal timescales, separately. We aim to (a) examine the timescale-dependency of the AMO–AMOC relationship and (b) understand the physics behind the AMOC–AMO relationship for each timescale. The remainder of this paper is organized as follows: Section 2 provides information of the model and data-processing method. In Section 3, we present the simulated and observed AMOC–AMO relationship for each frequency domain and expound the physical processes. Discussions and the summary are provided in Sections 4 and 5 respectively.

2 | DATA AND METHODS

In this study, version 1.3 of the LOch–Vecode-Ecbilt-CLio-agIsm model (LOVECLIM; Goosse et al., 2010), an Earth system model with intermediate complexity, is used. In LOVECLIM, a quasi-geostrophic atmospheric model (ECBilt; Opsteegh et al., 1998) using a T21 spectral truncation with 3 vertical levels is coupled with an ocean GCM (CLIO; Goosse and Fichefet, 1999) and a dynamic vegetation model (VECODE; Brovkin et al., 1997). CLIO solves the primitive equations with a horizontal resolution of 3° in the global domain, and explicitly simulates the dynamic-thermodynamic evolution of sea ice. Surface albedo is calculated in ECBilt using relative fractions of land, ocean, and sea ice in a grid, which are transmitted from CLIO, and the parameterization of surface turbulent heat fluxes are based on the classical bulk formulas.

The relatively simplified physics and economical spatiotemporal resolution of LOVECLIM provide two main
advantages, which makes the model adequate for the purpose of this study. First, while the model produces reasonable features of large-scale climate phenomena (Goosse et al., 2010), its intermediate complexity reveals the main causes of climate phenomena easily. Second, the efficient computational speed enables a sufficiently long simulation, which is essential for the investigation of long-term (e.g., multi-decadal) climate variability. Although some weaknesses are also raised, such as suppressed variability in the tropics and in the atmosphere due to the low resolution and quasi-geostrophic approximation in the atmospheric model, these major weaknesses are not considered to be crucial for our main research target.

Figure 1 presents the power spectra of the AMOC and AMO indices obtained from LOVECLIM. Here, the AMOC index is defined as the maximum of the meridional streamfunction below 500 m, north of 20°N in the Atlantic basin. The AMO index is computed as detrended, area-weighted SST anomalies averaged over 0–70°N in the Atlantic. The power spectrum of the simulated AMOC index (Figure 1a) indicates that LOVECLIM simulates the AMOC variability at a level similar to those of the CMIP5 models (Zhang and Wang, 2013), despite its simple model configuration. The spectral peaks of the AMO index (Figures 1b) are also well reproduced (Zhang and Wang, 2013). LOVECLIM also realistically captures the AMOC (Figure S1a) and AMO (Figure S1b) structures, although the spatial pattern (Figure S1b) bears some warm bias in the southeast of Greenland, compared to the observation (Clement et al., 2015).

In the AMOC spectrum (Figure 1a), there is a wide spectral gap between the inter-decadal and multi-decadal timescales. The AMO spectrum (Figure 1b) also exhibits a spectral gap between these two timescales, although it is not as clear as it is in the AMOC spectrum. Interestingly, in both the power spectra, pronounced peaks can be observed near the 20-, 40-, 60- and 80-year periods, and local minima can be observed near the 35- and 100-year periods. The similarity between the two spectra strongly indicates the possibility of a physical interaction between the AMOC and AMO. Because there exists a gap between the inter- and multi-decadal periods at around the 35-year period, the physical relationship at each timescale is worth exploring. To this end, we produce new time series of both the indices that contain only the inter-decadal and multi-decadal timescales by applying a 10–40-year and a 40–100-year band-pass filter, respectively. For the AMO index, the inter-decadal and the multi-decadal variabilities constitute 30.74% (0.00592°C²) and 18.99% (0.00366°C²) of the total variance (0.0193°C²), respectively. For the AMOC index, the inter-decadal and multi-decadal components account for 40.71% (0.96Sv²) and 11.54% (0.27Sv²) of the total variance (2.36Sv²), respectively. That is, the newly produced time series contain a substantial portion of the variability of the original time series. This will be discussed more in the next section.

To investigate the mechanisms of AMO, AMOC, and their interactions in the two different timescales, several oceanic state variables are regressed onto the inter-decadal and multi-decadal AMO and AMOC indices. High-frequency variations in the physical variables are eliminated by a 5-year moving averaging before the variables are used in the regression analysis. As the data loses its degree of freedom owing to the filtering process, we consider an effective sample size when testing the statistical significance of regression or correlation coefficients (Hsieh, 2009).

In Section 3, we also present the observed AMOC–AMO relationship. Because the observational data spans from 1866 to 2008, covering only 143 years, we focus on the inter-decadal variability. The observed AMOC

**FIGURE 1** Normalized power-spectrum densities (green line) of (a) the AMOC index and (b) the AMO index. No filter is applied for either index. Shaded areas represent inter-decadal (light red) and multi-decadal (light blue) domains, respectively. The pink lines denote red noise spectrum (solid), and 95% confidence level (dashed), respectively.
intensity is measured using the temperature-based AMOC index (Rahmstorf et al., 2015; Olson et al., 2018) because direct observation only began in 2004. The temperature-based AMOC index is defined as SST in the subpolar gyre region minus the areal averaged SST of the Northern Hemisphere ocean. For the observed AMO index, the global mean subsurface temperature anomaly (229.48–317.65 m) is subtracted from the North Atlantic mean to eliminate the effects of anthropogenic forcing. The subsurface temperature is used instead of the SST because the 20–30-year variability is more pronounced below the surface (Frankcombe et al., 2010). We use the ERSSTv4 dataset (Huang et al., 2015; Liu et al., 2015) for the SST and SODA reanalysis version 2.2.4 (Carton and Giese, 2008; Giese and Ray, 2011) for the subsurface ocean temperature.

3 | RESULTS

3.1 | Timescale dependency of the AMOC–AMO relationship

Figure 2 presents the lead–lag correlations between the AMO and AMOC indices for the inter-decadal, multi-decadal, and all timescales. Note that we use the term ‘all timescales’ for the simplicity even though high-frequency variations were eliminated in Figure 2a. When all timescales are considered together, the lagged correlation between the two indices is positive over a wide lead–lag range (Figure 2a). This indicates the possibility of a low-frequency external factor to govern the AMOC and AMO together, yet they may interact differently depending on the timescales. When the same analysis was conducted separately on the inter-decadal (Figure 2b, black line) and multi-decadal timescales (Figure 2c), we observed notably different lead–lag relationships between the AMO and AMOC. In the inter-decadal timescale, the lead–lag correlations indicate that the AMOC leads the AMO by approximately 7 years, whereas a negative phase of the AMOC follows a warm phase of the AMO with a lag of approximately 2 years. The lead–lag relationship in the inter-decadal timescale features an oscillatory behaviour between the AMO and AMOC. In Figure 2b, the lead–lag correlations for the inter-decadal timescale obtained from the observation are also shown. Similar to the LOVECLIM result, the observed relationship also indicates that the AMOC leads the positive AMO. However, the negative peak where the AMO leads the AMOC is not statistically significant for the observation, and the time delay by which the AMOC leads the AMO are different from the model. This discrepancy might have arisen partly from the absence of a sufficiently long record. The AMO–AMOC relationship in the multi-decadal timescale is considerably different from that in the inter-decadal timescale. In the multi-decadal timescale, the AMO and AMOC are almost in phase. Although the exact location of the positive peak is slightly biased toward the AMO leading, neither the location nor the magnitude of the peak is distinct from the zero lag, considering the timescale of interest. The multi-decadal relationship in the observation was not explored owing to the short data length. The results presented in Figure 2 highlight that the AMO–AMOC relationship is different in the inter-decadal and multi-decadal timescales, which cannot be
seen when all timescales are considered together in a lead–lag correlation analysis. In fact, positive correlations shown in all timescales can be seen as the oscillatory relationship in the inter-decadal timescale overlaid with the simultaneous positive relationship in the longer timescale. Subsequently, we investigate the AMOC–AMO relationships in the two timescales. One might cast doubt on the relevance of the correlation between filtered datasets, since the peaks may appear as artefacts from the filtering process (Trenary and DelSole, 2016; Cane et al., 2017). However, we note here that the filtered AMOC and AMO indices represent physical variation rather than being statistical artefacts, as our filters are selected to retain the dominant variabilities (Figure 1 and see also Text S1). Nonetheless, the periodicity may be more emphasized by the filter, resulting in repeated peaks in the lead–lag diagram. Therefore, we focus only on those peaks that are close to the zero-lag.

3.2 Inter-decadal AMOC–AMO relationship

The simulated relationship in the inter-decadal timescale presented in Figure 2b exhibits a possible oscillatory feature via an interaction between the AMOC and AMO such that strong AMOC leads warm AMO; the warm AMO later weakens the AMOC intensity. The positive correlation during the positive lag years suggests that a warming of the Atlantic Ocean is induced by the meridional heat transport (MHT) associated with the AMOC, and an approximate 7-year time delay in the AMO response is associated with the temporal evolution of inter-decadal AMOC. Figure 3 indicates that a strong meridional mass streamfunction anomaly, which initially occurs in the high latitude of about 55°N, migrates to the south while its strength weakens slightly (see also Figure S4). Such southward propagation of the AMOC anomaly, which has been frequently documented in modelling studies, is a result of its advection through the interior pathways (e.g., Zhang, 2010; Ba et al., 2014; Zhang and Zhang, 2015; Zhang et al., 2019). Along with this southward movement of the AMOC anomaly and the associated MHT (Figure S4), warm-SST anomalies also propagate southward (Figures S5 left panels). Thus, there arises a time delay between a mature phase of the AMOC and a basin-wide warming (AMO).

In this timescale, the AMO precedes the opposite phase of the AMOC by approximately 2 years. During a warm phase of the AMO, an anomalous warm SST reduces the surface density (Figures 4b and S6) in the AMOC sinking region (Figure 4a). Although it is known that the meridional density gradient in the Atlantic is positively correlated with the AMOC strength (Hughes and Weaver, 1994; Rahmstorf, 1996; Jackson and Wood, 2018), because the spatial structure of the AMOC in the inter-decadal timescale is rather confined to the Northern Hemisphere (Figure S4 left panels), its strength obviously relies more on the local density in the convection site (Figure S7a). Figures S7a and S7b indicate that the density changes induced by the AMO would hinder deep-water formation and thus reduce the AMOC, creating a negative peak at lag −2 years in Figure 2b. That is, their lead–lag relationship in Figure 2b is a result of an interactive oscillatory mode of the inter-decadal AMOC/AMO. The spectral peaks near 20 years shown in Figure 1 quite well fits the characteristic timescale of the oscillatory loop. That is, a positive phase of the AMOC leads a warm phase of the AMO by 7–8 years and the warm AMO induces an AMOC phase transition after 2 years, and thus it takes about 10 years for the half cycle of an oscillation. Therefore, it further reconfirms that the interaction between the AMOC and the AMO is a primary factor for their inter-decadal variability.

3.3 Multi-decadal AMOC–AMO relationship

Different from the inter-decadal timescale, there is almost no delay for the multi-decadal AMOC to warm the Atlantic basin as indicated by a significant positive correlation at around a lag of 0 (Figure 2c). Furthermore, unlike the inter-decadal timescale wherein southward migration of the AMOC causes asynchronous warming between different latitude bands, the AMOC in the multi-decadal timescale fluctuates with a large-scale feature covering the entire Atlantic basin with no significant latitudinal
displacement of the core in its life cycle (Figure S8 left panels). Thus, the heat transport of the AMOC (Figure S8 right panels) in the multi-decadal timescale over the North Atlantic basin is coherent with the basin-wide warming of the AMO (see also Figure S5 right panels). Such spatial coherence between the AMOC and the AMO results in a quasi-synchronous relationship between them.

Figure 2c also indicates that the AMOC and the AMO are negatively correlated at lag $-40$ and $30$ in the multi-decadal timescale. To verify whether a positive AMO induces a negative AMOC after 40 years, we conducted an AMO pacemaker experiment (Text S2). The AMO signal to drive the model was obtained from the control simulation (which is analysed throughout this study) so that it contains the multi-decadal variability. However, in this pacemaker experiment, multi-decadal variability in the AMOC was not reproduced (Figure S9). It means that the negative peak at lag $-40$ represents the periodicity of the data, not a lagged influence of the AMO on the AMOC. Given that the AMOC influences the AMO through the MHT with almost no time delay, the negative peak where the AMOC leads also reflects the spectral peaks at 70–80 years. In conclusion, a self-sustaining oscillation through interaction, present in the inter-decadal timescale, is absent in the multi-decadal timescale, and the AMO phase passively follows the AMOC phase.

4 | DISCUSSIONS

On the inter-decadal timescale, the oscillation is self-sustained by the interaction between the AMOC and AMO. On the multi-decadal timescale, however, some other factor to draw a phase transition of the AMOC is required for the semi-periodic variability (shown as multi-decadal peaks in Figure 1) to be sustained. It may be the inherent instability of the ocean (Weaver et al., 1991; Huck et al., 2001; Te Raa and Dijkstra, 2002; Lee and Wang, 2010) or may have arisen from interaction with atmospheric variability or the Arctic (Delworth et al., 1997; Delworth and Greatbatch, 2000; Dong and Sutton, 2005; Jungclaus et al., 2005; Hawkins and Sutton, 2008; Xu et al., 2019). As we focus on the AMOC–AMO interaction and their sequential relationship, the detailed mechanism of the AMOC variability has not been explored. Yet the lagged regression maps between the upper ocean density and the AMOC index (Figure S10) infer that interaction with the Arctic through East Greenland Current may be responsible for it.

In the previous studies, the multi-decadal variability of the AMO has been attributed to external forcing such as the Arctic and/or atmospheric variabilities (Belkin et al., 1998; Zhang and Vallis, 2006; Lin et al., 2019). However, in this study, the phase change of the AMO is essentially related to the thermal advection associated with the AMOC in both the timescales.

5 | SUMMARY AND CONCLUSIONS

While the coupled models bear some inconsistency in simulating lead–lag relationships of the AMOC and AMO (Zhang and Wang, 2013), this study attempts to better understand their relationship by taking the
timescale-dependency into account. Their relationship in the inter-decadal time scale is characterized by an interactive oscillator, whereas their in-phase relationship in the multi-decadal timescale is paced primarily by the AMOC variability. The key factor in the creation of such a difference is the variation in the spatiotemporal pattern of the AMOC. In the inter-decadal timescale, the southward migration of the AMOC and the associated SST anomalies cause the basin-wide warming of the North Atlantic to follow the AMOC peak. This phase lag, which is essential to the oscillatory relationship between the AMOC and the AMO, is absent in the multi-decadal timescale essentially because AMOC-related SST anomalies are stationary.

This timescale-dependency of the AMOC–AMO relationship has some important implications. Recent studies have reported frequency shifts in AMOC and AMO under climate changes (Cheng et al., 2016; Moore et al., 2017). Therefore, identifying the fundamental mechanisms of AMOC–AMO interactions in each frequency domain may be useful in understanding future climates, although we must note that anthropogenic forcing can modify the AMOC–AMO interaction (Tandon and Kushner, 2015).

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