Assessment of the Ability of CESM1 to Simulate the Atmospheric Teleconnection Excited by the Atlantic Multidecadal Variability in Summer

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Abstract

Observational analysis shows that the Atlantic Multidecadal Variability (AMV) is a major driver of climate variability in the Northern Hemisphere through a zonal atmospheric teleconnection extending from the North Atlantic Ocean and propagating eastward around the Northern Hemisphere. We studied the fidelity of model simulations in reproducing the observed summer AMV and the associated impacts on the Earth's climate by analyzing simulations using the National Center for Atmospheric Research Community Earth System Model Version 1 (CESM1), including CESM1 idealized and time-series pacemaker simulations, CESM1 large ensemble twentieth century uninitialized simulations and large ensemble initialized CESM1 decadal predictions. To further compare the fidelity of CESM1, we also analyzed large ensemble simulations from four other models. Our results suggest that the uninitialized large ensemble simulations from all models can produce an AMV time evolution and its regional climate impacts similar to the observations to certain degree. By initializing the observed oceanic condition in decadal prediction simulations, the simulated AMV and its regional impacts are closer to the observed ones than those in uninitialized ensemble simulations. In addition, the time-series pacemaker simulations that nudged the observed North Atlantic sea surface temperature anomalies produces spatiotemporal characteristics of the AMV and AMV climate impacts closer to the observed ones than the uninitialized simulations. We conclude that although coupled models can reproduce the observed AMV and its regional impacts, proper initialization and bias correction of the sea surface temperature spatial structure can significantly improve this capability. Further improvements in the fidelity of the simulated AMV depend on how to reduce model biases, especially the simulated teleconnections.

1. Introduction

In contrast with other ocean basins, in which the leading mode of variability is dominated by interannual variabilities, the observed Atlantic Ocean is dominated by a multidecadal variability with a period of about 60–80 years. This is often referred to as the Atlantic Multidecadal Variability (AMV; Delworth and Mann 2000; Enfield et al. 2001; Seidov et al. 2017). This variability is thought to be linked to low-frequency oceanic processes, such as the Atlantic Meridional Overturning Circulation (AMOC, Delworth et al. 1993; Delworth and Mann 2000; Latif et al. 2004; Knight et al. 2005; Yin and Stouffer 2007; Hu et al. 2012), local air–sea coupling (Wills et al. 2019) and stochastic atmospheric processes (Clement et al. 2015). The AMV may also have been modulated by volcanic (Otterå et al. 2010) and anthropogenic (Mann and Emanuel 2006; Booth et al. 2012) aerosols during the twentieth century (Si and Hu 2017). Using a partial coupling approach, Garuba et al. (2018a, b) found that the AMV is largely driven by oceanic variability, but its power is also affected by local air–sea coupling.

Many previous studies have suggested that the AMV can cause significant climate fluctuations in many regions across the globe (e.g., Ruprich–Robert et al. 2017). A positive phase AMV is suggested to induce a strengthened monsoon over Northern Africa and India and a weakened monsoon over South America (Monerie et al. 2019). In the Afro-Asian regions, a below-normal sea surface temperature (SST) in the North Atlantic (a negative AMV), such as that seen in the 1960s, led to a positive sea-level pressure

anomaly and a weakened summer monsoon over the Afro-Asian region (Liu and Chiang 2012), and vice versa for an above-normal SST (a positive AMV). This has been documented in many observational (Li et al. 2017; Yang et al. 2017; Han et al. 2018) and modeling (Zhang and Delworth 2006; Liu and Chiang 2012; Lin et al. 2019) studies.

The association of AMV with the North Atlantic storm track and eddy-driven jet in winter was reported by a recent study (Ruggieri et al. 2021). In the positive phase of AMV, the Atlantic storm track is usually contracted and less extended northward and the jet stream is shifted southward over the eastern Atlantic Ocean and vice versa for the negative phase of AMV. The AMV also plays a central role in determining the variability of the European climate in both boreal summer and winter through the atmospheric teleconnection (Qasmi et al. 2020, 2021). The variation of AMV leads to anomalously dry summers in northern Europe and wet summers in southern Europe during the 1960s–1980s (Sutton and Hodson 2005) and the opposite change in the 1990s (Sutton and Dong 2012). In East Asia, it appears to be that AMV can modulate the East Asian climate through two pathways: tropical and extratropical atmospheric teleconnection processes and the Rossby wave train (Monerie et al., 2021). In addition, the impacts of the AMV are not restricted only to the extra-tropics, but also expand throughout the tropics (Parsons et al. 2014; Li et al. 2015; Zhang and Kristopher 2017). Such as, the recent warming trend in Atlantic Ocean leads to an intensified Walker circulation, Pacific trade winds and eastern tropical Pacific cooling, which partly offset the global warming since the early 1990s (McGregor et al. 2014, 2018).

To produce these planetary-scale influences, the AMV acts as a source of climate variability in the Northern Hemisphere via a circum-global stationary baroclinic wave train, as identified in an observation-based study by Si and Ding (2016). This teleconnection provides a mechanistic explanation of the impacts of the AMV on regional climate variability in the Northern Hemisphere. Although evidence of AMV-induced climate variability has been identified in observations, it is still an open question as to whether the AMV and, more importantly, its influence on the regional and global climate, can be correctly simulated by climate models.

It is essential for correctly assessing climate variability and its origins that models are able to simulate the AMV faithfully because it is such an important source of variability in the Earth's climate. To assess this capability, we first analyzed two types of North Atlantic pacemaker simulations from the Community Climate System Model Version 1 (CESM1, Hurrell et al. 2013) to verify whether the AMV can generate a circum-global teleconnection wave pattern in model simulations (Boer et al. 2016). We then examined whether the AMV-induced teleconnection can be reproduced by a set of large ensemble experiments conducted by multiple Coupled Model Intercomparison Project Phase 5 (CMIP5) class Earth system models (ESMs) (the Multi-Model Large Ensemble Archive; MMLEA, www.cesm.ucar.edu/projects/community-projects/MMLEA/).

Lastly, we zoom into one model (CESM1) to perform a more detailed comparison among the initialized large ensemble decadal prediction simulations (CESM-DPLE; Yeager et al. 2018), the corresponding uninitialized large ensemble free-run twentieth century all-forcing ensemble simulations (CESM-LE;

Kay et al. 2015) and the ensemble North Atlantic pacemaker experiments to assess whether correctly initialized ocean conditions can give a better simulated AMV compared with the observations and whether the correction of the simulated North Atlantic SST biases can produce a better AMV teleconnection. We focus on the summer (June–July–August, JJA) season and evaluate how well the models can reproduce the observed time evolution of the AMV, the associated teleconnections and their impacts on summer rainfall and temperature.

The paper is organized as follows. Section 2 introduces the observed datasets, model simulations and analysis methods used in this study. Section 3 examines the AMV–induced atmospheric teleconnection for both the observations and simulations. Sections 4 and 5 investigate the effect of initialization on the simulation of the AMV and its associated teleconnection pattern, respectively. A brief summary and discussion are given in Section 6.

2. Observed And Modeled Data And Methods

a. Datasets

The SST dataset used in this study is taken from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST) dataset, Version 5 for the time period 1959–2016. The atmospheric pressure data are taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset for the time period 1959–2016 (Kalnay et al. 1996). The observed global precipitation data over land and oceans are obtained from the NOAA precipitation reconstruction dataset during the time period 1959–2016 (Chen et al. 2002). The observed surface air temperature (SAT) data are derived from the University of Delaware global SAT dataset from 1959 to 2016. The AMV index for both observations and model simulations is defined here as the area–weighted average of the SST over the North Atlantic between the equator and 65°N with the linear trend removed (Delworth and Mann 2000; Enfield et al. 2001).

b. North Atlantic idealized pacemaker experiments

A 30–member ensemble of the CESM1 idealized North Atlantic pacemaker simulation is used to investigate the impacts of internal component of AMV on the global atmospheric teleconnection (Meehl et al. 2021). In order to generate the idealized AMV pattern to which the model is restored (Ruprich–Robert et al. 2017), the internally generated part of observed decadal–time scale North Atlantic variability is separated from the externally forced part (Ting et al. 2009). First, the externally forced part of AMV is estimated by applying signal–to–noise maximizing empirical orthogonal function (EOF) to the CMIP5 multi-model ensemble using historical simulations for the 1870–2005 period and Representative Concentration Pathway 8.5 (RCP8.5) simulations for the 2006–2013 period. Hence the temporal component of the external–forced part of SST as time series of the global signal–to–noise EOF1 is generated, and the spatial pattern of the external–forced part is obtained by regressing the observed

global SST (the ERSST version 3) on the time series of EOF1. Second, the internally generated temporal component of AMV is derived from the residuals of observed North Atlantic (0–60° N, 75°–7.5° W) SSTs by subtracting the externally forced part. While, the internally generated AMV spatial pattern is then estimated by regressing the residuals of the observed SST onto the internally generated AMV index. These SST fields and time series are low-pass filtered before the regressions with a ten-year cut-off period. The idealized pacemaker simulations are under a constant external forcings at pre-industrial level, and consist of 30-member positive AMV (AMV+) and 30-member negative AMV (AMV–) runs. Every simulation is integrated for ten years during which the seasonal cycle of SST anomalies in the North Atlantic are held constant in time, while the SST in the rest of the globe freely to evolve in the coupled simulations (Meehl et al. 2021).

c. North Atlantic time-series pacemaker experiments

A 10-member ensemble of the CESM1 North Atlantic Ocean time-series pacemaker simulation is used, in which a fully restored observed SSTs anomalies (the ERSST version 3) is applied over the region 5–55°N of the North Atlantic, with two buffer belts along 0–5°N and 55–60°N. In these buffer zones, the fully nudged SST anomalies (at 5°N and 55°N) are gradually damped to zero (at 0° and 60°N) via a sine function of the latitude change. In this way, the observed evolution of North Atlantic SSTs is maintained in each simulation, with the SST in the rest of the globe freely to evolve in the coupled simulations. These simulations are branched on January 1, 1920 from a historical CESM1 simulations and run to 2013 with historical forcing from 1920–2005 and RCP8.5 future emissions scenarios from 2006 to 2013. Studies have shown that these time-series pacemaker simulations are able to reproduce the climate response to the observed SST forcing in the North Atlantic (Meehl et al. 2021; Yang et al. 2020).

d. MMLEA simulations

The MMLEA is a multi-model large ensemble intercomparison project including simulations from seven different CMIP5-class ESMs under time-varying external historical and future emissions scenarios forcings from 1850 to 2100 (Deser et al. 2020). Because the geopotential height and sea-level pressure is currently unavailable from three of the seven models, we only analyzed four of the models (CanESM2, CSIRO-MK, GFDL-CM and CESM1) (Table 1). There are 50 members for CanESM2 from 1950 to 2100 (Kirchmeier-Young et al. 2017), 30 members for CSIRO-MK from 1850 to 2100 (Jeffrey et al. 2013), 20 members for GFDL-CM from 1920 to 2100 (Sun et al. 2018) and 40 members for CESM1 from 1920 to 2100 (Kay et al. 2015).

The generation of these large ensembles differs slightly from one model to another. CESM1 and GFDL-CM use a micro-perturbation method by inducing round-off level errors into the atmospheric temperature field and keeping everything else identical, but CSIRO-MK use a macro-perturbation method by starting each ensemble member from a different time point in its 1850 control run. CanESM2 uses a mix of these two methods. The forcings used in these large ensembles are the time-evolving observed all-forcings

from 1850 to 2005 and RCP8.5 from 2006 to 2100 (Table 1). Deser et al. (2020 and references cited therein) provide more details on these large ensembles.

e. Initialized decadal prediction simulations

The decadal prediction simulations performed by CESM1 are a set of 40-member ensemble initialized simulations (CESM-DPLE) similar to the near-term hindcast experiments in CMIP5 (Taylor et al. 2012). All the ensemble members are forced by the same observed time-varying external forcings as in CESM-LE and the same ocean-sea ice initial conditions for each of the starting years. The ocean and sea ice initial conditions used in CESM-DPLE are derived from a coupled ocean-sea ice simulation forced by the Coordinated Ocean-Ice Reference Experiment (CORE) forcing data from 1954 to 2015 (Yeager et al. 2018). The initial conditions for the atmosphere and land are taken from the corresponding year of the CESM-LE simulations. To generate a set of 40-member large ensemble decadal prediction simulations, round-off level perturbations are added into the initial atmospheric conditions in a similar way to the free-run CESM-LE simulations. CESM-DPLE simulations are initialized on November 1 every year from 1954 to 2015 and are integrated forward for 122 months. Here, we use the mean of years 3–7 in the decadal prediction to represent the predicted state of year 5 and this is compared with the corresponding observations (Meehl and Teng 2014). In other words, we predict the climate state 5 year means at lead times of year 3–7 and compare this predicted climate state with year 5 in the observations.

f. Methods

The wave activity flux for stationary Rossby waves embedded in a zonally asymmetrical climatological-mean flow was diagnosed. This represents the directions of propagation of the wave energy (Takaya and Nakamura 1997). The horizontal components of the flux W can be expressed in pressure coordinates as

$$W = \frac{1}{2|U|} \left[\begin{aligned} &U(\psi_x'^2 - \psi' \psi_{xx}') + V(\psi_x' \psi_y' - \psi' \psi_{xy}') \\ &U(\psi_x' \psi_y' - \psi' \psi_{xy}') + V(\psi_y'^2 - \psi' \psi_{yy}') \end{aligned} \right] \quad (1)$$

where U and V represent the zonal and meridional basic flow velocity respectively, Ψ' denotes the perturbation geostrophic stream function, and x and y represent the zonal and meridional directions, respectively.

In addition to the wave activity flux, which is used to identify the propagation of Rossby waves from the Atlantic to Pacific oceans, pattern correlation and the root-mean-square-error (RMSE) were also used to

quantify how well different simulations are capable of reproducing the observed patterns of the atmospheric circulation, precipitation and SAT.

To extract the interdecadal signal, a low-pass filter (with a ten-year period cut off) is applied to the observation and model outputs to remove the interannual signals. The statistical significance of the regression and correlation analysis is assessed by means of the NCAR Command Language (<http://dx.doi.org/10.5065/D6WD3XH5>) function that based the bootstrapping method. In current study, all the simulation results from the MMLEA runs, initialized runs and pacemaker runs were computed from each member individually first, and then did the ensemble average.

3. Atmospheric Teleconnection Induced By The Amv

a. Observations

The observed low-pass filtered AMV index shows a remarkable interdecadal variability from 1959 to 2016. In general, the AMV index shows a positive–negative–positive fluctuation, with positive phases in the time periods 1959–1964 and 1997–2013 and negative phases in the time periods 1965–1996 and 2014–present (Fig. 1a).

As indicated in previous research (Si and Ding 2016), the AMV is capable of driving the climate variability in the Northern Hemisphere through exciting a circum-global Atlantic–Northern Hemisphere (ANH) teleconnection. This teleconnection can be identified from the regression of the AMV onto the 500–hPa geopotential height, which displays a prominent global zonal wave train pattern with five centers of action located over the North Atlantic, Western Europe, Eastern Europe, northern Asia and the western North Pacific (Fig. 1b). To demonstrate this ANH teleconnection pattern more clearly, the AMV is regressed onto the 500–hPa stream function in the Northern Hemisphere (Fig. 1c). It is clear that the ANH teleconnection pattern can also be observed in the stream function field. The positive stream function corresponds to the positive (anticyclonic) center of action and the negative stream function corresponds to the negative (cyclonic) centers in Figure 1b. The wave activity flux is calculated to explore the propagation of the wave energy associated with the ANH (Fig. 1c). The wave activity flux shows that the wave energy propagates northeastward from the subtropical North Atlantic to Western Europe and then propagates eastward through the Eurasian continent to the North Pacific Ocean. This result indicates that the AMV is the origin of the circum-global atmospheric teleconnection pattern.

The atmospheric circulation is equivalent barotropic in the extra-tropical sector of the North Atlantic (Figs. 1b and 1d). The barotropic dipole mode, with high pressure over the mid-latitude North Atlantic and low pressure to the west of the UK, resembles the eastern Atlantic atmospheric pattern. The eastern Atlantic atmospheric pattern is excited by changes in the stationary waves, which are associated with SST anomalies in the North Atlantic (Msadek et al. 2011). The wave energy related to the eastern Atlantic atmospheric pattern emanates globally from the North Atlantic along the mid-latitude westerly jet (Fig. 1c).

At lower levels, anomalous low pressures are located over North Africa, western Europe and northern Asia, whereas there are anomalous high pressures over the mid-latitude North Atlantic, eastern Europe and the western North Pacific (Fig. 1d). The low-pressure anomalies correspond to an inflow of moisture toward the center and increased cloudiness, leading to above-normal precipitation anomalies and below-normal SAT anomalies in most parts of western Europe north of 42°N, in North Africa between 5° and 20°N, in the area around Lake Baikal and in parts of East Asia (Figs. 1e and 1f), and vice versa for the anomalous high-pressure circulation. The high pressure over the western North Pacific and low pressure over East Asia enhance the East Asian summer monsoon, which results in the northward movement of the East Asian rain belt to the north of the Yangtze River (Guo 1983).

The anomalies in the observed atmospheric circulation, precipitation and SAT (Figs. 1b–f) are consistent with previous observational (Sutton and Dong 2012; Si and Ding 2016) and numerical studies (Cheng et al. 2007; Liu and Chiang 2012). For example, observational analysis has shown that the warming of the North Atlantic causes a large-scale high–low–high pattern of anomalous circulation over the North Atlantic and western and eastern Europe, respectively, and the anomalous trough located over western Europe contributes to a North–South dipole of climate over western Europe with drier and warmer conditions over the South and wetter and mild conditions over the North (Sutton and Dong 2012). A coupled model study has suggested that the cooler North Atlantic in the 1960s weakened the African and Eurasian summer monsoon via an ANH-like atmospheric teleconnection (Cheng et al. 2007). These studies suggest that the AMV is a major force in the ANH teleconnection and is capable of causing hemispheric-scale changes in the Earth's climate.

b. Simulation by the North Atlantic pacemaker experiment

The idealized North Atlantic pacemaker simulations indicate that, for AMV+ minus AMV–, the SST pattern in the North Atlantic is characterized by positive SST anomalies above 0.2°C over the tropical North Atlantic and above 0.4°C over the extra-tropical North Atlantic exhibiting the positive phase of internally-generated AMV (Fig. 2a). There are significant same-sign SST anomalies above 0.1°C over the western North Pacific, which resembles the negative phase of Pacific Decadal Oscillation. It is noteworthy that the internally-generated AMV generate the ANH teleconnection pattern extending from the North Atlantic to the western North Pacific (Fig. 2b, c), with a close resemblance to the observations. The idealized simulation captures well the meridional tripolar pattern over North Atlantic and other three centers of action over eastern Europe, East Asia and western North Pacific. Eventually, the idealized simulation reproduces well the wet and mild climate over North Africa and western Europe, dry and warm climate over eastern Europe and southern East Asia, and wet and warm climate over northern East Asia corresponding to the positive phase of AMV (Fig. 2d, e). These results suggest that the ANH teleconnection indeed driven by the low-frequency and internally-generated component of AMV.

Because the SSTs in the time-series pacemaker experiments are nudged toward the time-evolving observed SST anomalies in the North Atlantic, it is not surprising that these experiments can capture well

the observed variation in the SST anomalies in the North Atlantic (Fig. 3a). The simulated AMV index in the time-series pacemaker experiments is almost identical to the observations from 1959 to 2013, with the temporal correlation coefficient (TCC) reaching 0.99 and an RMSE of only 0.03 (Table 2). The time-series pacemaker experiment reproduces the ANH teleconnection pattern extending from the North Atlantic to the western North Pacific reasonably well, with a pattern correlation coefficient (PCC) of 0.19 (Fig. 3b, Table 3). The geographical positions of the action centers generally match the observed positions over the North Atlantic and western Europe, with an eastward shift of the action center over eastern Europe to the west of Lake Baikal. At the surface, the simulated sea-level pressure, precipitation and SAT anomalies also agree with the observations, with PCCs of 0.04, 0.37 and 0.61, respectively (Figs. 3c–e, Table 3). Physically, the negative sea-level pressure anomalies correspond to above-normal precipitation and below-normal SATs, and vice versa for the positive sea-level pressure anomalies, suggesting that the model can capture the basic physical processes well.

Despite these agreements, the teleconnection simulated in CESM1 is more biased further downstream than in the region directly over or near the North Atlantic, indicating that improvements are still needed for the model to be able to more accurately simulate the observed teleconnection patterns. Nevertheless, these results suggest that the AMV is capable of influencing the northern mid-latitude atmospheric anomalies and climate variability in the Northern Hemisphere in both the observations and numerical simulations (Sutton and Hodson 2005; Si and Ding 2016; Jiang et al. 2020).

c. Simulation by the MMLEA experiments

Figure 4 shows the AMV index simulated by the four models of the MMLEA (CanESM2, CSIRO-MK, GFDL-CM and CESM1). The models are generally capable of reproducing the observed positive-negative-positive phase variation of the AMV from 1959 to 2016. The TCC between the simulated AMV index in the MMLEA and the observations ranges from 0.44 to 0.69 with an RMSE <0.17, a number about five times larger than that in the CESM1 time-series pacemaker runs (Table 2).

The simulated ANH atmospheric teleconnection pattern in the MMLEA is compared with the observations. The MMLEA models are generally capable of producing an ANH-like teleconnection pattern from the North Atlantic through Eurasia to the western North Pacific, with shifts in the geographical positions of the action centers (left-hand panels in Fig. 5). The MMLEA multi-model mean generally capture the positive geopotential height anomalies over the mid-latitude North Atlantic and eastern Europe and the negative anomalies over western Europe and northern Asia associated with the ANH teleconnection pattern (Fig. 5e). Among the four MMLEA models, there are two or more models basically agree with the observed sign along the route of this teleconnection pattern. While more than three models reproduced the same sign with the observation over parts of North Atlantic and northern Asia. Compared with the observation, it can be seen that the negative anomalies over western Europe is weak and shift eastward. Moreover, the multi-model mean fail to capture negative geopotential height anomalies over Lake Baikal and positive geopotential height anomalies over northwest Pacific and

produce an anomalies over the Lake Baikal–Okhotsk Sea sector of opposite sign to the observation. Among the four models, the GFDL–CM shows the best performances in simulating the geopotential height anomalies in the Lake Baikal–Okhotsk Sea sector and bear a strong resemblance to the observations. The PCCs between the simulations and observations for the 500–hPa geopotential height in the northern mid-latitudes are better over the Eurasian continent than over the North Atlantic and are positively correlated in two (CanESM2 and GFDL–CM) of the four MMLEA models (Table 3), but are negatively correlated in CSIRO-MK and CESM–LE. The PCC is negative over the North Atlantic in nearly all models because they all produce a positive North Atlantic Oscillation (NAO)–like pattern, but there is a negative NAO–like pattern in the observations. Previous multi-model comparison of the AMV and its climate impacts (Medhaug and Furevik 2011; Ting et al. 2011; Ba et al. 2014) is model dependent. Our study also highlights the large discrepancies associated with the atmospheric teleconnection related with AMV simulated by the CMIP5–like experiments. Although the RMSEs for all models are not very different from that in the CESM1 time–series pacemaker simulations, the simulated teleconnection pattern in MMLEA is more biased than that in the CESM1 time–series pacemaker simulations (Table 4), either due to a biased pattern or the more significantly shifted geographical locations of the active centers.

For the corresponding northern mid-latitude wave–train–like sea–level pressure anomalies in association with the ANH (right–hand panels in Fig. 5), the PCCs between the model simulations and the observations are positive in two models (CanESM2 and GFDL–CM), with a PCC higher than the CESM1 time–series pacemaker runs (Table 3), but negative in CSIRO–MK and CESM–LE over the Eurasian continent. Over the North Atlantic, only GFDL–CM produces a strong positive PCC and the other three models produce a negative or zero PCC. These results indicate that although the models are capable of producing wave–train–like sea–level pressure anomalies, the exact locations of these anomalies differ from those in the observations, which calls for further improvements in the simulated atmospheric circulation pattern.

The models capture the low-level convergence–divergence–convergence pattern of the Eurasian continent seen in the observations, eventually leading to a wet–dry–wet pattern in precipitation and a mild–warm–mild pattern in the SAT (Fig. 6). Although CESM-LE produces a negative PCC with the observed precipitation, the other three models all produce a positive PCC, but less than that in the CESM1 time–series pacemaker runs (Table 3). The PCCs between the observed and modeled SAT anomalies are fairly similar among the models. Overall, pattern correlation analysis shows that the skill of the MMLEA models with respect to the AMV–induced precipitation and SAT teleconnection are generally higher than the skill for the geopotential height and sea–level pressure (Table 3). The higher PCC for the SAT may be a result of its lack of detailed regional patterns. A particularly noteworthy point is that the time–series pacemaker simulations show a higher PCC and lower RMSE than the MMLEA simulations (Tables 3 and 4), implying that the North Atlantic SST biases in the free–run models may have played an essential part in deviating the atmospheric circulation pattern and the associated surface climate from the observations. By correcting these SST biases, the CESM1 time–series pacemaker runs produce AMV–related teleconnection patterns significantly better than those in CESM–LE.

Nevertheless, the MMLEA models suggest that the AMV can generate a circum-global atmospheric teleconnection pattern extending from the North Atlantic and propagating eastward around the globe. The overall better performance of the time-series pacemaker runs in simulating the AMV and associated atmospheric teleconnection than the free-run MMLEA historical simulations can be attributed to the SST, which is close to the observed North Atlantic SST, further demonstrating that this circum-global atmospheric teleconnection pattern is closely related with the AMV.

4. Impacts Of Initialization On The Simulation Of The Amv

After the comparison between the time-series pacemaker simulations and the free-run MMLEA simulations, we turn our attention to the initialized large ensemble decadal prediction runs: the CESM-DPLE. The simulated AMV in these runs shows a similar variation to the observed data and their correlation coefficient reaches 0.67, with a statistical significance of 95% (Fig. 7a). The simulated phase transition for the first positive to negative phase is delayed by four years in CESM-DPLE relative to the observations (1970 instead of 1966), but is nearly the same as the observations for the negative to positive transition in the late 1990s. The CESM-DPLE misses the second positive to negative transition in 2012.

To further quantify the fidelity of the simulated AMV in CESM-DPLE, we compare the CESM-DPLE with CESM-LE and the CESM1 time-series pacemaker simulations. Note that CESM-LE includes only the observed external forcings (solar and volcanoes, greenhouse gases and anthropogenic aerosols), whereas CESM-DPLE includes not only the observed external forcings, but also an initial ocean-sea ice state that is close to the observations. The time-series pacemaker runs include the observed external forcings and the time-evolving almost unbiased North Atlantic SST. By comparing these three sets of simulations, we can identify the improvements in the simulation of the AMV and its influence on the summer climate as a result of better initial ocean-sea ice conditions and the unbiased North Atlantic SSTs under the same model configuration.

As shown in Table 2 and Figures 1a, 3a, 4d and 7a, the amplitude of the AMV index in CESM-LE is weaker than that simulated by CESM-DPLE, the time-series pacemaker runs and the observational dataset. The CESM-LE is capable of reproducing the positive-negative-positive fluctuation of the AMV, implying that the time evolution of the AMV in this period may have been strongly influenced by external forcings, such as anthropogenic aerosols (Mann and Emanuel 2006; Booth et al. 2012), but it has the lowest skill (low correlation), followed by CESM-DPLE and the time-series pacemaker runs (Table 2). Although the initialized CESM-DPLE performs better than the uninitialized CESM-LE in simulating the time evolution of the AMV in summer, the drift toward the model preferred state after the initialization depreciates the full benefit of the initialization. Because the North Atlantic SSTs are constantly nudged toward the observations in the time-series pacemaker runs, the nearly unbiased SSTs in the North Atlantic produce a nearly identical AMV to the observations (Table 2). Properly initialized simulations therefore increase the model's skills in predicting the observed climate in association to AMV to certain degree, as stated previously (Keenlyside et al. 2008; Meehl et al. 2016; Si et al. 2019).

5. Impacts Of Initialization On The Simulation Of Anh Teleconnection

The PCC between the simulated and observed ANH-like patterns is the best overall for the time-series pacemaker runs, followed by CESM-DPLE and CESM-LE (Tables 3 and 4). For example, the time-series pacemaker runs outperform the other two sets of large ensembles on all counts. Although the model used is identical for all the simulations, the different input conditions have a significant influence on the outcome—that is, the biased SSTs and ocean states in CESM-LE produce a less accurate AMV-related teleconnection pattern in the North Atlantic–Eurasia region, whereas the better ocean initial states in CESM-DPLE produce improved results and the nearly unbiased SSTs in the time-series pacemaker runs give results that are improved further. It can therefore be concluded that although the time-series pacemaker runs produce the best AMV-related teleconnection, the nearly unbiased SSTs still cannot correct all the intrinsic biases from the model. Further improvement in the simulated teleconnection therefore depends on how the model development team can resolve the biases not only in the air–sea coupling and ocean states, but also in the atmospheric dynamics.

A further detailed comparison between the simulations and observations shows that the simulated anomaly patterns from the North Atlantic to Europe for the 500-hPa geopotential height in the time-series pacemaker runs is similar to the observations, but that there is a large deviation in Asia. These biases become progressively worse from CESM-DPLE to CESM-LE, with the latter producing almost the opposite pattern to the observations (Figs. 1b-c, 3b-c, 5d, 5i and 7b-c). For precipitation, the anomalies in the time-series pacemaker runs are significantly more similar to the observations than the other two sets of CESM1 simulations (Figs. 1e, 3d, 6d and 7d). There are some improvements in the simulated precipitation anomaly in western Europe in CESM-DPLE compared with CESM-LE. Although the biases in the simulated SAT are the smallest among the other variables, CESM1 still has difficulty in capturing the detailed regional temperature patterns (Figs. 1f, 3e, 6h and 7e). These results are consistent with previous studies, which showed that the initialized simulations or SST-corrected simulations from coupled models demonstrate substantial skill in simulating SST anomalies in North Atlantic Ocean (van Oldenborgh et al. 2012; Marotzke et al. 2016; Keenlyside et al. 2008), whereas the skill is lower over the adjacent land areas (Doblas-Reyes et al. 2013; Meehl et al. 2014).

The simulated composite changes in precipitation and SAT were investigated during two AMV phase transitions: the mid-1960s (a positive to negative transition, left-hand panels in Figs. 8 and 9) and the late 1990s (a negative to positive transition, right-hand panels in Figs. 8 and 9). In general, the precipitation and SAT anomalies over North Africa, Europe and East Asia in the left-hand panels have roughly the opposite signs of those shown in the right-hand panels for both the observations and simulations, implying that the AMV is indeed the major cause of these shifts in climate.

A comparison between Figs. 1e and 1f indicates that, although the SAT and precipitation anomalies during the two phase transitions have a similar pattern, they still show clear differences, such as the precipitation anomalies over northern India–Tibet and the coastal regions of eastern China (Figs. 8a and 8e). Similar differences can be seen in the simulations (Figs. 8b–8h). For these phase transitions, the

simulated changes in precipitation in the time-series pacemaker runs are still better than in CESM-DPLE and CESM-LE, and CESM-DPLE is better than CESM-LE. For instance, the regional variations in precipitation are less in CESM-LE than in the other two sets of simulations. The results for the SAT anomalies are similar to those for precipitation. The basic relationship between the AMV and the regional climate explored here corroborates previous modeling studies (Sutton and Hodson 2005; Liu and Chiang 2012; Dong et al. 2016; Jiang et al. 2020), suggesting that CESM1 is capable of simulating these relationships between the AMV and regional climate variability.

6. Summary And Discussion

Our results show that the AMV is a major driver of climate variability in northern mid-latitude regions through a circum-global atmospheric teleconnection extending globally from the North Atlantic through Eurasia. CESM1 idealized and time-series pacemaker simulations in which the time-evolving SST anomalies in the North Atlantic are nudged to the observations show that the North Atlantic SST anomalies (AMV) generate a circum-global teleconnection closely resembling the observational pattern. During the positive AMV period, the geopotential height over North Africa, western Europe and northern Asia decreases, which increases summer precipitation and decreases the SAT over these regions. By contrast, the geopotential height and SAT increase over eastern Europe and the summer precipitation decreases, and vice versa for the negative AMV period. We evaluated the capability of the free-run MMLEA twentieth century historical simulations to simulate the AMV-induced atmospheric teleconnection and showed that the MMLEA is capable of generating a teleconnection pattern similar to the observations with a shift in the geographical locations of the action centers and an altered strength.

To more systematically evaluate the influence of ocean-sea ice initializations and bias-corrected SSTs over the North Atlantic, we analyzed four sets of CESM1 simulations: CESM1 idealized and time-series pacemaker runs, CESM-DPLE and CESM-LE. This comparison shows that an initial ocean-sea ice state close to the observations can improve the time evolution of the simulated AMV and the teleconnection pattern and that the bias-corrected SSTs make further improvements in the simulated AMV and its teleconnection. However, there is still a difference between the simulated and observed teleconnection patterns, even in the time-series pacemaker runs. These results suggest that further improvements in model dynamics and physics are needed for the models to be able to more faithfully simulate the AMV-related teleconnections.

Declarations

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Conflicts of interest/Competing interests.

The authors declare no competing of interests.

Availability of data and material.

All data used in this study are publicly available. The large ensembles simulations and North Atlantic pacemaker simulations are accessible via the National Center for Atmospheric Research (NCAR) Climate Data Gateway and the observational data are available through the respective institutions.

Code availability.

The figures were created by using the NCAR Command Language (<http://www.ncl.ucar.edu/>).

Authors' contributions.

Dong Si made the calculations and created the figures. Aixue Hu, Dabang Jiang, Dong Si and Xianmei Lang contributed to the interpreting results and writing the paper.

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Tables

Table 1

Details of the five simulations in the MMLEA project used in this study.

Model	Years	Ensemble size	Resolution (atmosphere/ocean)	Forcings
CanESM2	1950–2100	50	~2.8°×2.8°/~1.4°×0.9°	Historical, RCP8.5
CSIRO–MK	1850–2100	30	~1.9°×1.9°/~1.9°×1.0°	Historical, RCP8.5
GFDL–CM	1920–2100	20	~2.0°×2.5°/~1.0°×0.9°	Historical, RCP8.5
CESM1	1920–2100	40	~1.3°×0.9°/~1.0°×1.0°	Historical, RCP8.5

Table 2

Temporal correlation coefficient (TCC) and root–mean–square–error (RMSE) between the observed and simulated Atlantic Multidecadal Variability indices during the time period 1959–2013. The correlation coefficients with asterisks indicate that the significance level reaches 95%.

Experiment	TCC	RMSE
CanESM2	0.69*	0.12
CSIRO–MK	0.50	0.16
GFDL–CM	0.68*	0.16
CESM–LE	0.44	0.17
CESM–DPLE	0.67*	0.13
Time–series pacemaker run	0.99*	0.03

Table 3

Pattern correlation coefficient (PCC) between the simulated and observed Atlantic Multidecadal Variability–related summer 500–hPa geopotential height (Z500), sea–level pressure (SLP), precipitation and surface air temperature (SAT) during the time period 1959–2013.

Variable	Z500 (gpm/°C)	Z500 (gpm/°C)	SLP (hPa/°C)	SLP (hPa/°C)	Precipitation (mm/°C)	SAT
Domain	(20°– 65°N, 0°– 130°E)	(0°–65°N, 70°W–0°)	(20°– 65°N, 0°– 130°E)	(0°– 65°N, 70°W– 0°)	(10°–50°N, 0°–130°E)	(10°– 50°N, 0°– 130°E)
CanESM2	0.11	–0.56	0.19	0.00	0.01	0.67
CSIRO–MK	–0.32	–0.59	–0.45	–0.17	0.15	0.67
GFDL–CM	0.09	0.00	0.43	0.25	0.32	0.69
CESM–LE	–0.12	–0.09	–0.60	–0.16	–0.16	0.51
CESM–DPLE	–0.10	0.03	–0.21	0.15	0.32	0.68
Time–series Pacemaker run	0.19	0.37	0.04	0.21	0.37	0.61

Table 4

Root–mean–square–error (RMSE) between the simulated and observed Atlantic Multidecadal Variability–related summer 500–hPa geopotential height (Z500), sea–level pressure (SLP), precipitation and surface air temperature (SAT) during the time period 1959–2013.

Variable	Z500 (gpm/°C)	Z500 (gpm/°C)	SLP (hPa/°C)	SLP (hPa/°C)	Precipitation (mm/°C)	SAT
Domain	(20°– 65°N, 0°– 130°E)	(0°–65°N, 70°W–0°)	(20°– 65°N, 0°– 130°E)	(0°– 65°N, 70°W– 0°)	(10°–50°N, 0°–130°E)	(10°– 50°N, 0°– 130°E)
CanESM2	28.73	18.63	2.66	1.41	97.42	1.08
CSIRO–MK	30.77	17.76	2.97	1.53	86.76	1.08
GFDL–CM	28.81	15.20	2.53	1.22	79.16	0.98
CESM–LE	29.73	15.34	3.44	1.53	122.09	1.16
CESM–DPLE	29.16	15.00	2.81	1.28	79.25	0.88
Time-series pacemaker run	28.85	14.91	2.84	1.58	80.11	1.02

Figures

Figure 1

Observed low-pass filtered JJA mean AMV index and its related teleconnection pattern. (a) Low-pass filtered AMV index from 1959 to 2016 (units: °C). (b) Regression of the 500-hPa geopotential height eddy anomalies (units: gpm/°C) on the low-pass filtered AMV index. (c) Same as (b) except for the 500-hPa

stream function (shading; units: $10^{-6}/^{\circ}\text{C}$) and its corresponding wave flux (vectors; units: $\text{m}^2/(\text{s}^2\cdot^{\circ}\text{C})$). (d) Same as (b) except for the sea-level pressure (units: $\text{hPa}/^{\circ}\text{C}$). (e) Same as (b) except for the precipitation (units: $\text{mm}/^{\circ}\text{C}$). (f) Same as (b) except for the SAT (units: $^{\circ}\text{C}$). Values exceeding the 95% confidence level are stippled. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

(a). Five-year ensemble mean JJA mean SSTs (units: °C) for AMV+ minus AMV– simulated by the idealized pacemaker simulations. (b). Same as (a) except for the 500-hPa geopotential height eddy (units: gpm). (c). Same as (a) except for the sea-level pressure (units: hPa). (d). Same as (a) except for the precipitation (units: mm). (e). Same as (a) except for the SAT (units: °C). The stippling indicates statistical significance at the 95% confidence level according to Student's t-test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Simulated JJA low-pass filtered AMV index and its related teleconnection pattern by the North Atlantic time-series pacemaker experiment. (a) The low-pass filtered AMV index from 1920 to 2013 (units: °C). (b) Regression of the 500-hPa geopotential height eddy anomalies (units: gpm/°C) on the low-pass filtered AMV index. (c) Same as (b) except for the sea-level pressure (units: hPa/°C). (d) Same as (b) except for the precipitation (units: mm/°C). (e) Same as (b) except for the SAT (units: °C). Note: The

designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Simulated JJA low-pass filtered AMV index by the MMLEA experiments. Black lines represent the ensemble mean, and pink shading represents the ensemble spread. (units: $^{\circ}\text{C}$): (a) CanESM2; (b) GFDL-CM; (c) CSIRO-MK; and (d) CESM1.

Figure 5

Simulated JJA 500-hPa geopotential height eddy anomalies (left-hand panel; units: $\text{gpm}/^{\circ}\text{C}$) and sea-level pressure (right-hand panel; units: $\text{hPa}/^{\circ}\text{C}$) by the MMLEA experiments regressed on the low-pass filtered AMV index and their multi-model mean. The contours in Fig. e and f show the numbers of MMLEA models whose signs of the anomalies agrees with observed ones. The green and blue contours indicate the contour number = 2 and number = 4, respectively. “4” means that all models agree with observations, and “2” means that three models agree with observations. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the

part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Simulated JJA precipitation (left-hand panels; units: mm/°C) and SAT (right-hand panels) by the MMLEA experiments regressed on the low-pass filtered AMV index. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Simulated JJA low-pass filtered AMV index and its related teleconnection pattern by the CESM1 initialized decadal prediction simulations. (a) The low-pass filtered AMV index from 1920 to 2013 (units: °C). (b) Regression of the 500-hPa geopotential height eddy anomalies (units: gpm/°C) on the low-pass filtered AMV index. (c) Same as (b) except for the sea-level pressure (units: hPa/°C). (d) Same as (b) except for the precipitation (units: mm/°C). (e) Same as (b) except for the SAT (units: °C). Note: The

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Figure 8

Changes in the detrended summer precipitation for the climate shifts in the mid-1960s and late 1990s (units: mm). The left-hand panels are the shift in the mid-1960s defined as the difference between the means for 1970–1998 and 1959–1964. The right-hand panels are the shift in the late 1990s defined as the difference between the means for 1999–2016 and 1970–1998. The stippling indicates statistical significance at the 95% confidence level according to Student's t-test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its

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Figure 9

Changes in the detrended summer SAT (units: °C) for the climate shifts in the mid-1960s and late 1990s (units: mm). The left-hand panels are the shift in the mid-1960s defined as the difference between the means for 1970–1998 and 1959–1964. The right-hand panels are the shift in the late 1990s defined as the difference between the means for 1999–2016 and 1970–1998. The stippling indicates statistical significance at the 95% confidence level according to Student's t-test. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.