Is the interdecadal circumglobal teleconnection pattern excited by the Atlantic multidecadal Oscillation?

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ABSTRACT
The interdecadal circumglobal teleconnection (ID-CGT) pattern is the dominant circulation mode over the NH during boreal summer on the interdecadal time scale. Its temporal evolution is synchronous with that of the Atlantic Multidecadal Oscillation (AMO). In this study, through analyzing the results of sensitivity experiments using five AGCMs driven by specified AMO-related SST anomalies (SSTAs) in the North Atlantic, the authors investigate whether the ID-CGT is excited by the AMO. Two out of the five models simulate the barotropic stationary wave pattern located along the westerly jet, suggesting that the ID-CGT pattern should be excited, at least partially, by the AMO-related SSTAs. Model results suggest that the ID-CGT pattern plays a role in linking the AMO and NH summer land SAT perturbations on the interdecadal time scale.

1. Introduction
The Atlantic Multidecadal Oscillation (AMO) is an alternate basin-wide warming and cooling in the North Atlantic, with a periodicity of about 60–80 years (Delworth, Zhang, and Mann 2007; Kilbourne et al. 2008; Knudsen et al. 2011). It is one of the two leading modes of the internally generated interdecadal variability of the climate system (the other is the Interdecadal Pacific Oscillation) (Liu 2012). The AMO primarily results from the interdecadal variation of the northward meridional heat transport associated with the Atlantic meridional overturning circulation (Marini and Frankignoul 2014).

The AMO has considerable impacts on the summer climate in the NH. The positive phase of the AMO causes a warming of NH annual mean surface air temperature (SAT) (Zhang, Delworth, and Held 2007; DelSole, Tippett, and Shukla 2011), an increase in summer SAT in North America and Europe (Sutton and Hodson 2005), a decrease in summer precipitation over the U.S. Great Plains (McCabe, Palecki, and Betancourt 2004; Nigam, Guan, and Ruiz-Barradas 2011), and an increase in summer rainfall over the Sahel in northern Africa (Knight, Folland, and Scaife 2006; Mohino, Janicot, and Bader 2011). In addition, the AMO can also modulate the East Asian summer monsoon (Lu, Dong, and Ding 2006; Lu and Dong 2008; Yu et al. 2009) and the Indian summer monsoon (Goswami et al. 2006; Lu, Dong, and Ding 2006; Li et al. 2008; Wang, Li, and Luo 2009).

Based on 20CR data, Wu, Zhou, and Li (2016) found that, during boreal summer, AMO-related SST anomalies (SSTAs) correspond to a wave train-like teleconnection pattern located along the NH westerly jet. The teleconnection pattern possesses some striking dynamic properties that resemble those of the conventional circumglobal teleconnection (CGT) pattern defined on the interannual timescale (hereafter, IA-CGT), including zonal wavenumber five and the propagation along the waveguide associated with the westerly jet (Ding and Wang 2005). Given this resemblance, the interdecadal circumglobal teleconnection...
pattern is referred to as the ID-CGT pattern (Wu, Lin, and Zhou 2016). However, the ID-CGT pattern shows three features that make it distinct from the IA-CGT. Firstly, the five nodes of the ID-CGT shift westward relative to the latter by about 1/4 wavelength. Secondly, all five nodes of the ID-CGT exhibit barotropic structures, whereas the IA-CGT has a baroclinic node. Thirdly, the ID-CGT (IA-CGT) is highly correlated with the AMO (Indian summer monsoon precipitation) index (Wu, Lin, and Zhou 2016).

Though the temporal evolution of the ID-CGT is synchronous with that of the AMO, it is difficult to answer whether the ID-CGT is excited by the AMO purely through observational analysis. In this study, we explore this issue through analyzing the results of idealized numerical experiments. Our strategy is to assess the responses of multiple AGCMs to the specified AMO-related SSTAs in the North Atlantic. It is found that some models reasonably simulate a wave train-like teleconnection pattern located along the NH westerly jet, suggesting the ID-CGT pattern is partly forced by SSTAs associated with the AMO.

2. Data, analysis method, and experiment design

2.1. Observational and reanalysis data

The observational and reanalysis data used in the study include:

(1) Geopotential height from the 20CR data-set for the period 1920–2012 (Compo et al. 2011);
(2) Observational SST from the HadISSTv1.1 data-set for the period 1920–2012 (Rayner et al. 2003);
(3) Observational land SAT from the CRU TS3.21 data-set for the period 1920–2012 (Jones and Harris 2013).

2.2. Analysis method

Following Ting et al. (2009), the AMO index is defined as area-averaged SSTAs in the North Atlantic (0°–60°N, 80°W–0°) with the global warming signal removed through regression analysis (Figure 1(a)). The global warming signal is represented by the near global mean SST (60°S–60°N). We focus on interdecadal variability, and an 8-yr running average is applied to the AMO index to filter out high-frequency signals. The circulation and SAT anomalies associated with the AMO are obtained through regressing against the normalized 8-yr running averaged AMO index. Because it is difficult to accurately estimate the effective sample size of the running averaged AMO index, we use a non-parameter method—the random-phase test—to estimate the statistical significance of the regression analyses (Ebisuzaki 1997).

To investigate the propagation direction of wave energy associated with the ID-CGT, we analyze the wave-activity flux for stationary Rossby waves, as proposed by Takaya and Nakamura (2001). Its horizontal components in pressure coordinates are

\[
W = \frac{1}{2|\mathbf{u}|} \left\{ \bar{u} \left( \psi'^2 - \psi'^2_{xx} \right) + \bar{v} \left( \psi'^y \psi'^y - \psi'^y \psi'^y_{xy} \right) \right\}
\]

Here, overbars and primes denote mean states and deviations from the mean states, respectively; Subscript \( x \) and \( y \) represent zonal and meridional gradients; \( \mathbf{u} = (u, v) \) denotes horizontal wind velocity; \( \psi \) represents eddy stream functions.

2.3. Numerical experiment

The idealized AGCM experiment results used in the study are from the experiments organized by the U.S. CLIVAR drought working group (Schubert et al. 2009). The AGCMs were driven by various constructed idealized SSTs. The original objective of these experiments was to investigate the physical mechanisms linking SST changes to drought. The five AGCMs participating in the project were NASA NSIPP1, NCEP GFS, LDEO/NCAR CCM3, NCAR CAM3.5, and GFDL AM2.1 (Schubert et al. 2009).

The experiments used in the study include: (1) a control run forced with seasonally varying climatological SST (named the PnAn run); and (2) a sensitivity run forced with SSTAs in the North Atlantic related to the positive phase of the AMO superposed on the seasonally varying climatological SST (named the PnAw run). The AMO-related SST anomaly was obtained by applying a rotated EOF analysis on the annual mean near global SST during 1901–2004. Because the AMO is an internally generated interdecadal mode, its spatial pattern is not very sensitive to the extraction method. The pattern correlation coefficient between AMO-related SSTAs used in the experiments and that in Figure 1(b) reaches 0.78 in the red box. Nearly all models were integrated for at least 50 years, except for the NCEP GFS runs, which were integrated for only 36 years. During the integrations, the boundary conditions had an annual cycle, but no interannual variations. However, interannual variability is still generated in atmospheric models due to various nonlinear processes. Hence, the outputs of the last 30 years of the model simulations used in the analyses are independent of each other and basically equivalent to 30-member ensembles. The differences between the PnAw and PnAn runs represent the models’ responses to...
the AMO-related SSTAs. The significances of the models’ responses are examined using the Student’s t-test.

3. Results

The AMO-related SSTAs show a basin-wide warming/cooling in the North Atlantic, with tropical and extratropical branches centered over the tropical North Atlantic and Labrador Sea, respectively (Figure 1(b)), consistent with previous studies (e.g. Sutton and Hodson 2005; Gastineau and Frankignoul 2015). The AMO-related SSTAs correspond to an ID-CGT pattern in the upper troposphere during boreal summer, which is located along the NH westerly jet, with a zonal wavenumber 5 pattern (Figure 2(a)). The wave energy associated with the ID-CGT propagates eastward along the waveguide associated with the westerly jet, indicating the importance of the role of extratropical atmospheric dynamics in the maintenance of the ID-CGT pattern. The five nodes of the ID-CGT are centered over eastern Europe, southwest of Baikal, the northwestern Pacific, and the western and eastern coasts of North America, respectively (Figure 2(a)). All five nodes possess barotropic structures (Figure 2), indicating that the ID-CGT is not associated with tropical convection anomalies like the conventional IA-CGT pattern, because the tropical convective heating tends to drive baroclinic modes in terms of the Gill model (Gill 1980). In the upper troposphere, the ID-CGT pattern is dominated by positive geopotential height anomalies (Figure 2(a)); whereas in the lower troposphere, the magnitudes of the alternating positive and negative anomalies are comparable (Figure 2(c)). The zonal mean component of the ID-CGT pattern intensifies with height (figure not shown).

To investigate whether the ID-CGT pattern is excited by the AMO, we examine the responses of the five AGCMs to the specified AMO-related warm SSTAs in the North Atlantic. As shown in Figure 3, two of the five models (NCAR CAM3.5 and GFDL AM2.1) reasonably reproduce a well-organized wave train-like pattern confined within the NH westerly jet. The wave pattern of CAM3.5 exhibits a zonal wavenumber 4 pattern and is completely out of the phase with the ID-CGT pattern derived from the 20CR data (Figure 3(a)). Hence, the pattern correlation of NH extratropical 200 hPa geopotential height (Z200) anomalies (30–70°N) between NCAR CAM3.5 and 20CR is only 0.15. However, the simulated wave pattern holds some dynamic properties that are consistent with the ID-CGT derived from 20CR, including the wave energy...
propagating eastward along the waveguide associated with the westerly jet and circumscribing the entire NH (Figure 3(a)), and the barotropic vertical structures of the four nodes of the wave pattern (Figure S1).

The wave pattern of GFDL AM2.1 exhibits a wavenumber 5 pattern (Figure 3(c)). The longitudes of the three nodes over the Eurasian continent and northwestern Pacific are generally consistent with those in the ID-CGT pattern, while the other two nodes over North America and the North Atlantic are not exactly in phase with the latter (Figure 3(c)). The pattern correlation of NH extratropical $Z_{200}$ anomalies between GFDL AM2.1 and 20CR reaches 0.65. The wave energy associated with the wave pattern propagates eastward from the eastern North Atlantic to the northwestern Pacific (Figure 3(c)). Nearly all nodes show barotropic vertical structures except for that centered in the northeastern Pacific (Figure S2). Though the models’ responses show some weaknesses, the results of CAM3.5 and GFDL AM2.1 suggest that the barotropic stationary wave train-like pattern propagating along the westerly jet can be partly excited by the AMO-related SST forcing.

The atmospheric responses to extratropical SST forcing largely project on the atmospheric internal variability, which is primarily shaped by the interactions between transient eddy and large-scale flow (Kushnir et al. 2002). This explains why none of these models reproduce atmospheric circulation anomalies excited by the AMO perfectly.
highly consistent with observations. One discrepancy is that the cold SAT anomaly in Central Asia is weaker than observed.

4. Conclusion and discussion

The ID-CGT pattern is a stationary teleconnection pattern on the interdecadal time scale. It is located along the westerly jet and exhibits a zonal wavenumber 5 pattern, resembling the conventional IA-CGT pattern. All of the five nodes of the ID-CGT pattern hold barotropic vertical structures, suggesting that it is not excited by tropical convective heating like the conventional IA-CGT pattern. Though correlation analysis has indicated that the ID-CGT is closely associated with the AMO, it remained unknown as to whether the ID-CGT is excited by the AMO. In this study, we investigated this issue through analyzing the results of idealized numerical experiments. Five AGCMs were driven by specified AMO-related SSTAs in the North Atlantic, coordinated by the U.S. CLIVAR drought working group. The analysis shows that two out of the five models (NCAR CAM3.5 and GFDL AM2.1) can reproduce the
wave patterns located along the westerly jet, supporting the notion that the ID-CGT is, at least partially, driven by AMO-related SSTAs. The models’ responses also show some weaknesses. For NCAR CAM3.5, the wave pattern exhibits a zonal wavenumber 4 pattern and is not in phase with the ID-CGT pattern derived from the 20CR data. For GFDL AM2.1, though the simulated wave pattern exhibits a zonal wavenumber 5 pattern, only three nodes over the Eurasian continent and northwestern Pacific are in phase with the ID-CGT. It has been reported that external forcing factors only trigger midlatitude atmospheric circulation perturbation, while the spatial pattern and maintenance are largely determined by the internal dynamics of interactions between waves and the mean state (e.g. Ding et al. 2011). Thus, we should not assume that the wave pattern excited by the AMO is exactly in phase with the observation. Which aspects of the basic state determine the shape of the ID-CGT pattern deserves further study through analyzing simulations by more models.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This work was jointly supported by the National Basic Research Program of China [grant number 2012CB955202], the National Natural Science Foundation of China [grant numbers 41005040 and 41023002], and the R&D Special Fund for Public Welfare Industry (Meteorology) [grant number GYHY201506012].

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