Interdecadal circumglobal teleconnection pattern during boreal summer

Bo Wu,1,2* Jianshe Lin,1,3 and Tianjun Zhou1,2
1State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2Joint Center for Global Change Studies (JCGCS), Beijing, China
3University of Chinese Academy of Sciences, Beijing, China

Abstract

A new atmospheric teleconnection pattern on the interdecadal time scale, interdecadal circumglobal teleconnection pattern (ID-CGT pattern), is identified. The ID-CGT pattern dominates the interdecadal variability of the Northern Hemisphere (NH) extratropical circulation during boreal summer. The ID-CGT pattern has a great climate effect and can cause an alternatively positive and negative pattern of the NH mid-latitude land surface temperature anomalies. Compared with its counterpart on the interannual time scale (IA-CGT pattern), the ID-CGT pattern shows following three distinctive features. Firstly, although both ID-CGT and IA-CGT patterns show zonal wavenumber-5 structures, the former nodes shift westward relative to the latter by about 1/4 wavelength. Secondly, all the five nodes of the ID-CGT pattern possess barotropic structures, unlike the IA-CGT, which has a baroclinic node. Thirdly, the ID-CGT pattern is associated with the Atlantic multi-decadal oscillation, whereas the IA-CGT pattern is with the Indian summer monsoon precipitation anomalies.

Keywords: decadal variability; atmospheric teleconnection; AMO

1. Introduction

Circumglobal teleconnection (CGT) pattern is one of two dominant modes of the Northern Hemisphere (NH) extratropical upper-tropospheric atmospheric circulation anomalies during boreal summer on the interannual time scale (Ding and Wang, 2005). It exhibits a wave-like structure with wavenumber 5 and all the five nodes are confined within the waveguide associated with the NH westerly jet stream (Ding and Wang, 2005; Ding et al., 2011; Wang et al., 2012). The CGT pattern is excited by the Indian summer monsoon rainfall anomalies (Lin, 2009; Ding et al., 2011) and maintained by extratropical atmospheric internal dynamics (Yasui and Watanabe, 2010; Ding et al., 2011). The CGT pattern has been identified as one of the major predictability sources of the NH extratropical atmospheric circulation (Wang et al., 2009; Lee et al., 2010, 2011). However, the studies of the CGT pattern are so far confined to the interannual or shorter time scales.

Recently, a wave-like circulation pattern along the NH mid-latitude westerly jet stream was found to be associated with the interdecadal variability of the East Asian summer monsoon (Wu et al., 2016). The result inspired us to investigate whether the CGT pattern exists on the interdecadal time scale. Furthermore, if the interdecadal CGT (hereafter ID-CGT) pattern exists as hypothesized, what differences are there with the conventional CGT pattern on the interannual time scale (hereafter IA-CGT pattern)? In this study, we show evidences that the ID-CGT pattern is an intrinsic mode of the interdecadal variability of extratropical atmospheric circulations.

2. Data and method

Datasets used in the study include: (1) circulation fields from the Twentieth Century Reanalysis (20CR) dataset for the period of 1920–2012 (Compo et al., 2010); (2) observational sea surface temperature (SST) from the HadISST 1.1 dataset for the period of 1920–2012 (Rayner et al., 2003); and (3) observational land surface temperature from the University of Delaware’s Air Temperature database (v3.01) for the period of 1920–2010 (Willmott and Matsuura, 2012).

We identify the ID-CGT pattern through an objective and consistent way with that for the IA-CGT pattern. Major analysis processes include following three steps. Firstly, the Lanczos filtering method is used for time scale separation. A total of 8-year low-pass (high-pass) filtering is applied to the raw data to obtain low-frequency (LF) [high-frequency (HF)] fields. We also try filtering with window widths of 7 and 9 years. The results are not sensitive to the selection of window width (figure not shown). In addition, variability associated with the nearly global mean SST (60°S–60°N), which is the proxy of the global warming, are removed explicitly in the LF fields through a linear regression analysis is applied to the June–September (JJAS) mean.
Interdecadal CGT pattern

Figure 1. (a) Standard deviation of JJAS-mean 8-year low-pass filtered Z200, in which the signals associated with the global warming are removed through a regression analysis (shading, units: m) and climatological 200 hPa zonal wind (contour, units: m s\(^{-1}\)). (b) As in (a), but for 8-year high-pass filtered Z200.

LF and HF 200 hPa geopotential height (Z200) in the latitudinal band of 0°–70°N, respectively. The first mode of LF Z200 and the second mode of HF Z200 represent the ID-CGT and IA-CGT pattern, respectively, as shown below. Thirdly, other variable anomalies associated with the ID-CGT and IA-CGT patterns are obtained through regressing onto the corresponding principal component (PC) time series.

The statistical significance of the regression analyses is estimated using a ‘random-phase’ test developed by Ebisuzaki (1997), which is constructed based on a Monte Carlo simulation (details are in the Appendix S1, Supporting Information).

3. Results

Figure 1 shows the spatial distributions of the standard deviation of the LF and HF Z200. Both the LF and HF Z200 have a strong wave-like oscillation band along the jet stream, approximately 30°–70°N. However, oscillation centers of the Z200 are different between the two time scales, suggesting that LF and HF mid-latitude circulation anomalies are distinct. The magnitude of the LF standard deviation is about 70% of the HF over the band of 30°–70°N.

We applied EOF analyses to LH and HF Z200 over the NH (0°–70°N), respectively. For the interdecadal (interannual) time scale, the first (second) EOF mode, which account for 48.5% (13.7%) of total LF (HF) variance, is dominated by a zonal wave train along the NH jet stream (Figures 2(a) and 2(a)). Hence, we take the first (second) EOF mode of the LF (HF) Z200 as the ID-CGT (IA-CGT) pattern, and corresponding PC time series as the time series of the ID-CGT (IA-CGT) pattern.

Both the ID-CGT and IA-CGT patterns have five nodes. For the ID-CGT pattern, the five nodes are located at the eastern coast of North America, eastern Europe, northern East Asia, western North Pacific and western coast of North America, generally corresponds to the centers of the LF Z200 standard deviation (Figures 1(a) and 2(a)). In contrast, for the IA-CGT pattern, the five nodes are located at eastern North Atlantic, Caspian Sea, northeastern East Asia, central North Pacific and eastern North America. The correspondence between the nodes of the IA-CGT pattern and the centers of the HF Z200 standard deviation is much lower than that on the interdecadal time scale, especially for the standard deviation centers over the North Atlantic and Europe (Figures 1(b) and 2(b)). The spatial distributions of the contributions of the ID-CGT and IA-CGT patterns to the LF and HF variances are investigated (Figure 2(c) and (d)). All the nodes of the ID-CGT pattern account for more than 50% of the local LF variances. In contrast, for the IA-CGT pattern, only nodes over the East Asia and central North Pacific account for more than 40% of the local HF variances. We also estimate the variance contributions of the two modes to the raw (unfiltered) Z200 (Figure 2(e) and (f)). The spatial distributions of the variance contributions for the raw data are generally consistent with those for the filtered data, but magnitudes are much smaller (Figure 2(c)–(f)). The ID-CGT (IA-CGT) accounts for...
15.3% (6.1%) of the total variances of the NH raw Z200 (0°–70°N).

It is worth noting that the IA-CGT pattern is obtained through a maximum covariance analysis (MCA) in Ding et al. (2011). To check the reliability of the results derived from the EOF, we also conducted the MCA using 20CR, which extracts dominant modes explaining the greatest covariance between HF NH (0°–90°N) Z200 and HF tropical (15°S–30°N) precipitation. The obtained first MCA mode corresponds well to the second EOF mode of the HF Z200, with correlation coefficient between their time series reaching 0.79 (Figure 2(h)), which is statistically significant at the 5% level. In addition, the IA-CGT pattern derived from the 20CR for the period of 1920–2012 by using the two different methods generally resemble the CGT pattern in Ding et al. (2011) for the period 1948–2009, indicating that the 20CR is reliable in the extra-tropical atmospheric circulation.

To investigate the differences in the three-dimensional structure between the ID-CGT and IA-CGT patterns, we show the corresponding 200, 500 and 850hPa geopotential height anomalies (Figure 3). For the IA-CGT pattern, four out the five nodes exhibit barotropic structures, except for the node extending from north of the Indian peninsula northeastward to the

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northern East Asia (right panel of Figures 3 and S1(f)), consistent with the CGT pattern in Ding and Wang (2005) and Ding et al. (2011). On the basis of this characteristic, Ding et al. (2011) proposed that the CGT pattern is excited by the Indian summer monsoon precipitation anomalies during La Nina developing phase (Figure 3(h)), and then maintained by barotropic instability of the mid-latitude basic flow and propagation of wave energy along the wave guide associated with the westerly jet stream (Figure S1(b) and (d)). In the 20CR, the correlation coefficient of the IA-CGT time series with the contemporary observational All-Indian Rainfall Index (AIRI) (data from ftp://www.tropmet.res.in/pub/data/rain/iitm-regionrf.txt, Kothawale et al., 2006) is 0.44, reaching the 5% significance level.

The wave energy associated with the ID-CGT pattern also propagates eastward along the wave guide associated with the NH stream jet, consistent with the IA-CGT pattern (Figure S1(c) and (d)). However, the vertical structure of the ID-CGT pattern is different from that of the IA-CGT pattern. All five nodes of the ID-CGT pattern exhibit barotropic structures (left panel of Figures 3 and S1(e)), suggesting that the ID-CGT pattern is excited by different mechanisms from the...
IA-CGT pattern. To investigate what forcing factors responsible for the ID-CGT pattern, we show the associated SST anomalies (SSTAs) (Figure 3(g)). The North Atlantic is covered by basin scale warm SSTAs, which have two centers, located in the Labrador Sea and the tropical North Atlantic, respectively, resembling the spatial pattern of the Atlantic multi-decadal oscillation (AMO) (e.g. Kushnir, 1994; Kerr, 2000; Delworth et al., 2007). Meanwhile, the time series of the ID-CGT pattern is highly correlated with the AMO index, with correlation coefficient reaching 0.68, passing 5% significance test (Figure 2(g)). Here the AMO index is defined as JJAS-mean LF area-averaged SST in the North Atlantic (0°–60°N, 0°–80°W) minus nearly global mean SST (60°S–60°N), following Trenberth and Shea (2006).

The IA-CGT pattern tends to influence climate along its path (Ding et al. 2011). We compare the land surface air temperature (SAT) anomalies associated with the IA-CGT and ID-CGT patterns (Figure 4). The land SAT anomalies in the NH middle latitudes derived from the 20CR show alternatively positive and negative anomalies for both the IA-CGT and ID-CGT patterns. The warm (cold) anomalies generally correspond to overlying anticyclone (cyclone) anomalies, although their spatial phases zonally shift slightly. As a result, the wave-like SAT anomalies associated with the ID-CGT pattern shift westward relative to those associated with the IA-CGT pattern by about 1/4 wavelength due to the spatial phase shift between the ID-CGT and IA-CGT patterns. Observational land SAT anomalies derived from the Delaware dataset are generally consistent with those from the 20CR, supporting that the ID-CGT and IA-CGT patterns derived from the 20CR are reliable. The distinctions between 20CR and Delaware are also evident. Firstly, the cold anomalies over the East Asia associated with the ID-CGT pattern derived from the 20CR are contrary to warm anomalies from the Delaware. Secondly, all the negative anomalies in the Delaware are not as strong and significant as those in the 20CR in amplitude for both the time scales. What causes the distinctions deserve further study. On the other hand, the percentage of the LF (HF) variances of the land SAT associated with the ID-CGT
(IA-CGT) mode is calculated (Figure 4(e) and (f)). The ID-CGT-related SAT anomalies account for more than 30% of the LF variances in the eastern coast of North America, Europe and northern East Asia. Comparing with the ID-CGT, the contribution of the IA-CGT-related land SAT to the HF variances is much smaller, consistent with the smaller variance contributions of the IA-CGT mode relative to the ID-CGT mode.

This study is primarily based on the 20CR reanalysis dataset, which just assimilated observational surface pressure and sea level pressure and thus can cover the entire 20th century. It has been demonstrated that the 20CR can realistically reproduce the conventional IA-CGT pattern, including its dynamic properties, implying the reliability of the ID-CGT derived from it. The robustness of the ID-CGT pattern and its insensitivities to the datasets and analysis methods are further verified from following four aspects.

1. We applied an EOF analysis to the 8-year low-pass filtered Z200 (global warming signal is not removed as above), the second EOF mode corresponds to the ID-CGT pattern (Figure S2(a)), with its PC time series highly correlated with the ID-CGT time series \( (r = 0.76, \text{Figure S2(b)}) \).

2. A MCA analysis is applied to the LF fields between NH mid-latitude Z200 and SST in the North Atlantic (Figure S3). The first MCA mode explains 71% of the squared covariance. The mode involves the ID-CGT pattern in the Z200 field and the AMO in the SST field, indicating that the ID-CGT pattern is coupled with the AMO.

3. The EOF analysis was applied to the 8-year low-pass filtered Z200 from the JRA-55 reanalysis dataset (Ebita et al., 2011), which covers the period of 1958–2012. The second mode corresponds to the ID-CGT pattern, with locations of the five positive nodes highly consistent with those derived from the 20CR (Figures 2(a) and S4(a)). The corresponding PC time series is highly correlated with the simultaneous AMO index \( (r = 0.82, \text{Figure S4(b)}) \).

4. A MCA analysis is applied to the LF fields between NH mid-latitude Z200 from the 20CR and underlying observational land SAT from the Delaware (Figure S5). The first MCA mode accounts for 76% of the total squared covariance. The spatial distribution of the Z200 anomalies exhibits an ID-CGT-like pattern (Figure S5(a)). Corresponding expansion coefficient time series is highly correlated with the time series of the ID-CGT derived from the EOF analysis \( (r = 0.97, \text{Figure S5(c)}) \). The results indicate that the interdecadal variability NH summer mid-latitude land SAT is dominated by the ID-CGT.

4. Summary

In the study, we revealed that the interdecadal variability of the summertime NH extratropical atmospheric circulation is dominated by a global-scale stationary barotropic wave-like pattern along the jet stream with zonal wavenumber 5. Because of its resemblances with the conventional CGT pattern on the interannual time scale (IA-CGT), the wave-like pattern is referred to as the ID-CGT pattern. We demonstrated that the ID-CGT and IA-CGT patterns can be extracted through a consistent EOF analysis for Z200 on two different time scales. The contribution of the ID-CGT pattern to the variances of the NH raw (unfiltered) Z200 is far larger than that of the IA-CGT pattern (15.3 vs 6.1%).

Although the ID-CGT and IA-CGT patterns show some similarities, such as zonal wavenumber 5 structure and locations of action centers along the westerly jet stream, they have distinctive characteristics on following aspects. Firstly, the ID-CGT pattern shifts westward relative to the IA-CGT pattern by about 1/4 wavelength, consistent with the phenomenon that the locations of the major variability centers of the NH mid-latitude atmospheric circulation are different between interannual and interdecadal time scales (Figure 1). Secondly, the ID-CGT pattern is tightly associated with the AMO, whereas the IA-CGT pattern is with the tropical forcing from the Indian summer monsoon precipitation anomalies. Thirdly, all the five nodes of the ID-CGT pattern exhibits barotropic structure, while the IA-CGT has a baroclinic node located to the north of the Indian peninsula, suggesting that the ID-CGT pattern should not be driven by the tropical forcing as the IA-CGT, although the AMO-related SSTAs have a tropical component.

The ID-CGT pattern can modulate land SAT along it path. The anticyclonic (cyclonic) anomalies correspond to underlying warm (cold) anomalies. Previous studies have noted that the positive phase of the AMO can increase the NH mean surface temperature (e.g. Zhang et al., 2007; DelSole et al., 2011), and cause warm anomalies over the North America and Europe during boreal summer (Sutton and Hodson, 2005). Our results reveal a complete picture of the impact of the AMO on the NH extratropical land SAT during boreal summer, that is, the impacts of AMO on the NH local SAT rely on the spatial phase of the ID-CGT pattern.

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Supporting information

The following supporting information is available:
Appendix S1. Supporting information.

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