The relationship between the Arctic Oscillation and ENSO as simulated by CCSM4

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ABSTRACT

The correlation between the Arctic Oscillation (AO) and ENSO reflects the strength of the interaction between climate systems in the low and high latitudes. Based on the long-term (501 years) control simulation of CCSM4, the authors investigated the linkage between the AO and ENSO in boreal winter. Based on the correlation coefficients between them, the authors divided the entire period into two groups: one that included the years with statistically significant correlations (G1), and the other the years with insignificant correlations (G2). In G1, the AO-related atmospheric circulation pattern resembles the ENSO-related one. The Aleutian Low (AL) acts as a bridge linking these two modes. In G2, however, the AO and ENSO signals are confined to the mid-high and mid-low latitudes, respectively. There is no significant linkage between the AO and ENSO in boreal winter, showing a low correlation coefficient. Further analysis suggests that changes in the climatological features, including the strengthened AO, the negative Pacific Decadal Oscillation phase, and the weakened AL, may be responsible for the enhanced relationships.

1. Introduction

Internal climate interactions between the low and high latitudes are important for regional climate variations. One example of such interaction is that between the Arctic Oscillation (AO) and ENSO. ENSO is the strongest signal at interannual timescales, and it can robustly influence regional climate in the mid-low latitudes, such as the East Asian monsoon region (Alexander, Bladé, and Newman 2002; Wang 2002; Wang, Wu, and Fu 2000; Webster and Yang 1992). The AO, or its Atlantic counterpart, the North Atlantic Oscillation, is a dominant atmospheric mode in the northern high latitudes that can exert significant influence on the Eurasian and African climate (e.g. Gong and Ho 2003; Gong, Wang, and Zhu 2001; McHugh and Rogers 2001; Sun and Wang 2006, 2012; Sun, Wang, and Yuan 2008; Thompson and Wallace 2001; Zhou 2013; Zhou and Cui 2014; Zhou and Wang 2015).

Actually, the relationship between the AO and ENSO represents the collaboration of, and competition between, climate systems in the high and low latitudes. Therefore, it has critical implications for global and regional climate variations (e.g. Fraedrich and Müller 1992; Greatbatch and Jung 2007; Jia, Lin, and Derome 2009). Previous studies have revealed interdecadal changes in the relationship between the AO and ENSO (e.g. Greatbatch, Lu, and Peterson 2004; Li, Wang, and Liu 2014). Li, Wang, and Liu (2014) showed that the Aleutian Low (AL) acts as a bridge in the strengthening relationship between the AO and ENSO in January after the mid-1990s.

In the present study, a long-term pre-industrial simulation by CCSM4 (Muñoz et al. 2012) was used to explore the interdecadal variations in the relationship between the AO and ENSO, and associated atmospheric circulation.

2. Data and methods

CCSM4 is a global coupled climate model with a 1°, 26-level atmosphere coupled to a 1° (down to 1/48 in the equatorial tropics), 60-level ocean and state-of-the-art sea-ice and land-surface schemes (Gent et al. 2011). The 501-year control simulation was conducted with no interannual variations in external forcing agents, and greenhouse gas and
tropospheric sulfate aerosol concentrations were fixed at pre-industrial (1850) levels. Thus, there was no long-term trend in the control simulation. Additionally, the changes in the AO and ENSO connection were mainly caused by the internal variability of the climate system in this study.

The variables used included SLP, surface air temperature (SAT), wind fields, and SST. In this study, the ENSO index was defined as the areal mean SST in the Niño3.4 region (5°S–5°N, 120°–170°W). The AO index was defined as the leading principal component of monthly SLPs north of 20°N (Thompson and Wallace 1998). Here, we focus on the boreal winter season (i.e. December–February). The sign of the AO index was reversed (−AO) before calculating the spatial correlation patterns to facilitate the comparison between AO-related and ENSO-related signals.

Prominent interdecadal changes can be found in the 21-year running correlation between the AO and ENSO indices (Figure 1). To perform composite analysis, we grouped years into those with statistically significant (G1, 129 years) and insignificant (G2, 136 years) AO–ENSO correlations. Group G1 included years with correlation coefficients greater than the 95% confidence level (−0.41), while group G2 included years with correlation coefficients smaller than −0.2. The criterion of −0.2 was used to eliminate marginal effects of running correlation and keep G2 clear of the AO–ENSO relationship, as well as to obtain a sample size of G2 comparable with that of G1.

3. Results

Large-scale significant positive correlations between −AO and SLP are evident over northern high latitudes in both G1 and G2 (Figures 2(a) and (b)). For group G1, correlations are opposite across the meridian line (east, positive; west, negative) in the low latitudes, resembling warm ENSO signals (Figures 2(a) and (e)). In group G2, however, there is no significant correlation between the AO index and SLP over the Maritime Continent and Indian Ocean. At the same time, the negative correlations over the northern and eastern tropical Pacific become weaker than those in G1 (Figure 2(b)). For the −AO and SAT, positive correlations can be observed over the eastern tropical Pacific (Figure 2(c)), suggesting a warm ENSO pattern during the negative AO phase. However, there is no ENSO signal during the negative AO phase in G2 (Figure 2(d)). In G1, the correlation patterns between the ENSO index and SLP (Figure 2(e)), as well as between the ENSO index and SAT (Figure 2(g)) are both similar to the −AO-related SLP and SAT patterns (Figures 2(a) and (c)). However, the −AO-related SLP and SAT are stronger than their ENSO-related counterparts over the polar region, but weaker over the lower latitudes. In G2, significant correlations exist, mostly in the mid-low latitudes, while almost no significant correlations exist in the polar region.

Because the correlations with wind fields in the lower and upper levels present similar patterns, we have shown those in the upper level, which show stronger signals. In G1, −AO is significantly related to an anomalous anticyclone–cyclone–anticyclone wave-train pattern from the northern high latitudes through the North Pacific to the tropical Pacific (Figure 3(a)). The ENSO-related patterns in G1 (Figure 3(c)) are very similar to the −AO patterns (Figure 3(a)), with the exception of weaker correlations in the high latitudes and higher correlations in the mid-low latitudes. A negative AO can induce significant easterly anomalies in the midlatitudes, leading to significant cyclonic anomalies in the North Pacific and anticyclonic anomalies in the northwestern Pacific in G2 (Figure 3(b)). However, no robust signals can be found in the eastern tropical Pacific. Similarly, a warm ENSO can induce significant circulation anomalies over the tropics, as well as cyclonic anomalies over the North Pacific (Figure 3(d)). However, there are only weak anomalies over the high latitudes (Figure 3(d)). This suggests that the connection between the AL and both the AO and ENSO is enhanced in G1 compared with G2, which validates the AL bridging effect linking the AO and ENSO (Li, Wang, and Liu 2014).

To determine why there are differences in the relationship between the AO and ENSO, as well as any connections with the atmospheric circulation in G1 and G2, we analyzed the climatological differences in SLP, SAT, and wind fields between G1 and G2 (Figure 4). Statistically significant negative SLP anomalies are evident in the north of the Eurasian continent corresponding to a positive AO
anomaly in G1 (Figure 4(a)). Positive SLP anomalies appear over the North Pacific, though the values are not statistically significant. In the SAT fields, significant warming is observed over an area spanning from Northeast Asia to the central North Pacific, which is accompanied by cooling to the east (Figure 4(c)). This distribution resembles a negative Pacific Decadal Oscillation (PDO) pattern. Lower-level (not shown) and upper-level (Figure 4(e)) winds show...
are consistent with the internal decadal changes in the climate system, such as an anomalous positive AO, negative PDO phase, and weakened AL. However, the underlying mechanisms for internal decadal changes are still unclear. Both ENSO and the AO have statistically significant implications for the winter East Asian climate (e.g. Chen et al. 2013; Gong, Wang, and Zhu 2001; Wang, He, and Liu 2013; Zhou, Chen, and Zhou 2013). The connection to the East Asian climate varies and accompanies changes in AO–ENSO relationships. In periods with insignificant AO–ENSO interactions, the ENSO signals dominate East Asian temperature (Figure 2(h)), while the AO signals can only be found over small areas in northern East Asia (Figure 2(d)). Conversely, the influence of the AO on East Asian temperature becomes stronger during periods with significant AO–ENSO interactions (Figure 2(c)); in the meantime, the impact from ENSO becomes weaker (Figure 2(g)). These phenomena indicate that the implications of predicting ENSO for East Asian winter temperature, the success of which derives mainly from the ENSO phase, may become increasingly difficult.

significant westerlies occurring over northern Eurasia; this indicates a positive AO. Meanwhile, anticyclonic anomalies appear over the North Pacific, indicating a weakened AL. However, no systematic anomalies can be found in the climate variables in group G2.

4. Summary and discussion

Using data from the control experiment conducted by CCSM4, we separated years based on the presence of significant (G1) or insignificant (G2) AO–ENSO relationships. Composite analysis showed that AO- and ENSO-correlated patterns are different in G1 and G2. Connections with atmospheric circulation were statistically significant in both low and high latitudes in G1, while in G2 significant correlations were confined to the mid-high latitudes for AO and the mid-low latitudes for ENSO. In G1, the ENSO signal can propagate northward to the high latitudes, and the AO signal can propagate southward to tropical areas. The interactions between climate systems in the low and high latitudes are enhanced in G1, and the AL is likely to act as a bridge in the AO–ENSO linkage. The changes in climatological fields may be responsible for the different connections with the atmospheric circulation, such as the anomalous negative geopotential height over northern Eurasia, anomalous warming in the North Pacific, and the weakened AL. These changes in the background circulation are consistent with the internal decadal changes in the climate system, such as an anomalous positive AO, negative PDO phase, and weakened AL. However, the underlying mechanisms for internal decadal changes are still unclear.

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Figure 4. The climatological difference between G1 and the entire period (left column) and between G2 and the entire period (right column) for the (a, b) SLP, (c, d) TAS, and (e, f) 200 hPa wind field. The maximum zonal wind in (e) is 1.21 m s⁻¹.

Note: Dotted areas show the statistically significant values at the 90% confidence level.

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