Interannual Variation of the Asian-Pacific Oscillation

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Abstract

Previous studies have identified an Asian-Pacific Oscillation (APO) teleconnection pattern, which exhibits an out-of-phase relationship in the summer tropospheric temperature with warming over the Eurasia and cooling over the Northern Pacific and the Northern America, and vice versa. But the interannual variation of this teleconnection remains obscure. This study points out that the APO is associated with the second empirical orthogonal function (EOF) mode of the interannual anomalies of boreal summer tropospheric temperature, which accounts for 13.7% of total variance. Heat budget analysis shows that the seesaw-temperature distributions are resulted from different processes. For the Eurasia region, the warming (cooling) is contributed by the adiabatic heating (cooling) process due to downward (upward) anomalies. For the Northern Pacific region, the temperature variation is mainly contributed by zonal advection associated with interannual zonal wind perturbation acting on the climatological temperature gradient. Composite analysis shows the interannual zonal wind perturbation is related to the sea surface temperature anomalies over the equatorial eastern Pacific. Numerical experiments with an atmospheric general circulation model also demonstrate this relationship.

Key words: Atmospheric teleconnection; Eurasia- Pacific; Boreal summer; Atmospheric temperature

1.Introduction

The teleconnections in the Northern Hemisphere (NH) during boreal summer have received much attention, because they act as a significant source of climate variability and predictability over the NH extratropics (e.g., Ding and Wang 2007; Lee et al. 2014; Ha et al. 2012; Zhang and Zhou 2012; Wu et al. 2016a; Wang et al. 2013). They have been documented to modulate surface air temperature in both the tropics and extratropics (Ding et al. 2011, Wu et al. 2016b), rainfall (Nitta and Hu 1996; Kosaka et al. 2011), tropical cyclone activity (Choi et al. 2010; Kim et al. 2012) and synoptic-scale variabilities (Li et al. 2014). Moreover, they have also been invoked in numerous studies of climatic extreme events, such as 2009 cool summer over northern Central Asia, East Asia and central North America (Ha et al. 2012), the 1988 drought and the 1993 flood over North America (e.g., Trenberth et al. 1988; Trenberth and Guillemot 1996). Hence, it is conceivable that an improved understanding of the global teleconnections is of great utility and economic value.

Previous studies have detected different teleconnection patterns in NH during boreal summer. For example, Barnston and Livezey (1987) pointed out three significant teleconnection patterns: North Atlantic Oscillation, a subtropical zonal mode, and a single-centered Asian monsoon mode. A Eurasian teleconnection pattern along the westerly jet stream was also recognized (e.g., Lu et al. 2002). A meridional dipole-like vorticity pattern over the western Pacific and the Philippine Sea features the Pacific-Japan (PJ) teleconnection pattern (Nitta 1987, Kosaka and Nakamura 2006). By analyzing monthly anomalous geopotential height at 200 hPa, Ding and Wang (2005) identified a circumglobal teleconnection (CGT), which is primarily a zonally oriented wave train along the westerly waveguide and is in association with the Indian summer monsoon rainfall anomaly. They later revealed a western North Pacific-North

America (WPNA) pattern (Ding et al. 2011), which features a wave train emanating from the western Pacific monsoon trough and following a great circle. El Niño–Southern Oscillation (ENSO) cycle is shown to play a role in the wave structures (Ding et al. 2011).

More recently, based on analysis of seasonal mean [June–August (JJA)] anomalous temperature averaged over 500hPa – 200 hPa, Zhao et al. (2007) identified an Asian-Pacific oscillation (APO) pattern which is characterized by a zonal seesaw of tropospheric temperature in mid-latitudes of the Asian-Pacific region. When the troposphere is warming in the mid-latitudes of the Asian continent, it is cooling in the mid-latitudes of the central and eastern North Pacific as well as in North America and the North Atlantic Ocean, and vice versa. It reflects an out-of-phase relationship between Asia and the North Pacific; the intensity of which have an influence on the tropical cyclone activities over the western North Pacific (WNP) and movement of Mei-yu front (Zhao et al. 2011a). The APO index shows multiple time scale variability, including interannual, decadal and multi-decadal variations (Zhao et al. 2010; Zhao et al. 2012a). The formation of the lower-frequency of APO (e.g., decadal) is suggested to be due to the zonal vertical circulation caused by a difference in the solar radiative heating between the Asian continent and the North Pacific. The Asian land (including the Tibetan Plateau) heating anomalies is the main contributor, while the sea surface temperature (SST) anomalies over the Pacific Ocean do not exert strong influence (Zhao et al. 2012b; Zhao et al. 2011b; Zhou et al. 2010).

Although the previous studies have made some progress in understanding the APO, some questions still remain unsolved. For example, how prominent is the APO pattern in the interannual variability of the extratropical NH circulation? What factors lead to the zonal seesaw pattern on interannual time scale? Is it the same as in the

decadal time scale? With these questions in mind, we conduct this study to revisit this phenomenon.

The rest of this paper is organized as follows. The datasets and methods are described in section 2, the dominant modes of interannual variation of tropospheric temperature and its association with APO is examined in section 3, heat budget is conducted for the two main centers related to APO respectively in section 4 to understand the physical mechanism underlying the out-of-phase relationship. Finally, a summary is shown in section 5.

2.Data and methods

This study uses the monthly ERA-40 reanalysis with a horizontal resolution of 2.5×2.5 (Uppala et al. 2005) and the monthly SST from the HadISST dataset with a resolution of 1×1 (Rayner et al. 2003) during 1958-2001. In this study, interannual anomalies of summer tropospheric temperature is defined as JJA mean temperature averaged over 500 hPa - 200 hPa, which has been subject to removal of climatological annual cycle and linear trend. Note that we didn't artificially remove the zonal average temperature, which was performed in Zhao et al. (2007), to avoid overestimating the zonal asymmetric components. To reveal the loadings of the APO on the interannual variation of extratropical NH atmosphere, an area-weighted empirical orthogonal function (EOF) analysis is conducted over the temporal correlation matrix of the interannual anomalies of summer tropospheric temperature over the NH (20°N-55°N, 20°E-40°W).

To understand the formation of the zonal seesaw pattern of the interannual temperature anomalies, we diagnose the temperature heat budget equation as

$$\frac{\partial T}{\partial t} = -\mathbf{V} \cdot \nabla T + \omega \left(\frac{RT}{c_p P} - \frac{\partial T}{\partial p} \right) + \frac{Q_1}{c_p} \quad (1)$$

where T denotes temperature, $\mathbf{V}$ horizontal velocity vector, ω vertical pressure velocity, c_p denotes the specific heat at constant pressure, R the gas constant, L the latent heat of condensation. The term on the left hand side (lhs) of the equation denotes temperature tendency. The first term on the right hand side (rhs) represents horizontal advection of temperature, the second term adiabatic heating/cooling processes induced by vertical motion and the third term diabatic heating/cooling processes including radiation latent heating, surface heat flux and subgrid-scale processes. Q_1 is calculated from residual term of daily temperature equation as in Yanai (1973).

3. Major modes of interannual variability of the summer tropospheric temperature anomalies and its association with APO

Figures 1a,c present the first two EOF modes of the JJA-mean temperature anomalies averaged over 500hPa – 200 hPa. They account for 28.7% and 13.7% of the total variances, respectively, and can be distinguished from each other and the rest higher modes according to the criteria of North et al. (1982) (see Fig. 2).

The first EOF mode (EOF1) displays zonally symmetric signals over the global mid-latitudes as well as with wave structures embedded, indicating a consistent temperature change in NH extratropics. Comparing the pattern in Fig. 1a with CGT

pattern revealed by Ding and Wang (2005), it is found that the structure of this NH extratropical teleconnection is similar to that of the CGT.

The second EOF mode (EOF2) is characterized by a zonal dipole structure with areas of positive loadings observed over Eurasia and negative loadings over the Pacific and the North America. The out-of-phase relationship shown in EOF2 is similar to the APO pattern revealed by Zhao et al. (2007). Furthermore, the standardized time series of PC2 shows a significantly correlation coefficient (0.84) with the detrended APO index defined in Zhao et al. (2007). This indicates that the EOF2 mode indeed corresponds to the APO teleconnection. Our results suggest that the APO on interannual time scale is associated with the second dominant mode of the interannual temperature anomalies over NH and accounts for 13.7% of the total variances. Note that Zhao et al. (2010) have suggested that the APO is associated with the first EOF mode of upper-tropospheric temperature anomalies and account for 27% of the total variances. The difference is because they have artificially deducted the zonal mean from the temperature field before applying EOF analysis and the zonal dipole mode is overestimated.

4. Mechanisms for the zonal asymmetric structure of temperature anomalies

To further understand the formation of the EOF2 pattern or the APO, we separately address the causes for the temperature anomalies over the Eurasia and over the North Pacific in the following sections. Two boxes covering the temperature anomaly centers are selected to be focused on (i.e., (30°N-50°N, 60°E-120°E) and (20°N-40°N, 180°-120°W), see rectangles in Fig. 1c). We chose these two boxes because they are very close to the regions for the original definition of the APO index

(Zhao et al. 2007). Moreover, the positive-index years and the negative-index years are selected according to the standardized time series of PC2 with its values beyond 1 (-1) (see Table 1). Then, composite results are obtained by the difference between the average of the positive-index years and the average of the negative-index years (positive-index years minus negative-index years), and reflect the case with warming over the Eurasia and cooling over the North Pacific and the North America.

4.1 Causes of warming over the Eurasia

Figure 3 displays the time evolution of composited temperature anomalies averaged over the Eurasia box and its time tendency. As expected, apparent positive anomalies appear during JJA. The maximum warming tendency is found in May. We therefore conduct heat budget analysis of the composited temperature tendency in May to reveal the dominant processes that lead to the warming tendency.

Relative contributions of each budget terms are shown in Fig. 4. It is found that the positive temperature tendency is contributed by the adiabatic process while the horizontal advection and diabatic processes all play an opposite role. Fig. 5a presents the composite of pressure velocity profile averaged over the Eurasia box. Most of troposphere exhibits downdraft motion. As downdraft motion would warm the atmosphere by adiabatic process, the positive temperature tendency over the Eurasia in May is due to downward anomalies.

4.2. Causes of cooling over the North Pacific

Figure 6 displays the time evolution of composited temperature anomalies averaged over the North Pacific box and its time tendency. As expected, apparent negative anomalies appear during JJA. The maximum cooling tendency is found in

June. We therefore conduct heat budget analysis of the temperature tendency in June to reveal the dominant processes that lead to the cooling tendency.

Relative contributions of each budget terms are shown in Fig. 7a. The negative tendency is contributed by the horizontal advection and diabatic processes while the adiabatic process tends to result in positive tendency. As shown in Fig. 5b, there are downward anomalies in the upper troposphere and upward anomalies in the lower troposphere. The downdraft motion in the upper troposphere could induce adiabatic warming and diabatic cooling at the same time, as latent heat release related to convection could be suppressed by downdraft motion. As is inferred from Fig. 7a, the total effect of the downdraft motion over the North Pacific region is to increase the positive temperature tendency. Therefore, the horizontal advection term is considered to dominate the cooling process. Furthermore, we decompose the horizontal advection term as follows

$$(-\mathbf{V} \cdot \nabla T)' = -\bar{u} \frac{\partial T'}{\partial x} - \bar{u}' \frac{\partial \bar{T}}{\partial x} - \bar{u}' \frac{\partial T'}{\partial x} - \bar{v} \frac{\partial T'}{\partial y} - \bar{v}' \frac{\partial \bar{T}}{\partial y} - \bar{v}' \frac{\partial T'}{\partial y}, \quad (2)$$

where a bar denotes climatological average and a prime denotes interannual perturbation which is obtained by removal of annual cycle and linear trend. As shown in Fig. 7b, the dominant contributor for the composited cold horizontal advection in June is the interannual zonal wind perturbation acting on the climatological temperature gradient.

To understand the physical mechanism for the cold advection, we present the composite of 500-200 hPa averaged horizontal wind perturbations and multi-year mean temperature in June in Fig. 8. It is found that over the North Pacific box are

strong easterly anomalies. As a strong temperature trough exists in the eastern part of the box, the easterly wind could induce cold horizontal advection.

Then, what causes the strong easterly anomalies over the North Pacific box? Note that the easterly anomalies are associated with a cyclonic gyre centered at (20°N, 180°E), we therefore intend to understand the formation of the cyclonic gyre. Fig. 9 shows the composited SST anomaly and 850-hPa wind anomaly in June. The SST anomaly shows a La Niña-like pattern with cold SST anomaly over the equatorial eastern Pacific. Strong easterly anomalies are observed over the equator; and a pair of anticyclonic gyres (with marks of “A”) is observed flanking the equator to the west of the coldest SST anomaly pool. Meanwhile, in the upper troposphere apparent westerly anomalies are observed over the equator as well as a pair of cyclonic gyres (with marks of “C”, see Fig. 8). Based on the observed features, it is possible that the upper-level cyclonic gyres and lower-level anticyclonic gyres are due to Gill response to the underlying cold SST anomaly (Gill 1980). Note that significant positive SST anomaly is also observed in the mid-latitude North Pacific region and one may suspect that it could also impact the overlying atmospheric circulations. However, it has been demonstrated that the formation of such a warming pattern is mainly due to atmospheric forcing associated with the surface anticyclonic circulation while SST’s impact on atmosphere is weak (Wang et al. 2012; Wang et al. 2013).

To prove or disapprove our hypothesis that the upper-tropospheric cyclonic gyres are due to La Niña-like SST anomaly forcing, we use atmospheric general circulation model (AGCM) ECHAM (v4.6) (Roeckner et al. 1996) at T42 horizontal resolution to design numerical experiments. In addition to the control run (CTRL), which was forced by the monthly climatological SST field, -1 K SST cooling was added on the SST forcing field of June over the box located at the equatorial eastern Pacific ocean

(15°S~10°N, 160°E~80°W) (see rectangles in Fig. 9) in the sensitivity experiment. In both experiments, model was integrated for 30 years and results from the last 20 years were analyzed. The difference of wind fields in June between the average from the CTRL run and that from the sensitivity run represents response to the cold SST anomaly over the eastern Pacific. Fig. 10 shows the upper-level wind response obtained from the experiments. A pair of cyclonic gyres (marked with “C”) is found flanking the equator, and in the key box over the North Pacific, there is strong easterly anomaly. The above numerical experiment results suggest that the cooling of tropospheric temperature over the North Pacific region is related to the cold SST anomaly over the equatorial eastern Pacific.

5. Conclusion

In this study, we examined the dominant modes of the interannual variation of summer tropospheric temperature over the mid-latitude Northern hemisphere (NH) with the ERA-40 reanalysis. The first EOF mode is similar to the circumglobal teleconnection (CGT) pattern while the second EOF mode is associated with the Asian-Pacific Oscillation (APO). The APO reflects an out-of-phase relationship in the summer tropospheric temperature with warming (cooling) over the Eurasia and cooling (warming) over the Northern Pacific and the Northern America. It accounts for 13.7% of the total variances of the interannual variations of mid-latitude NH temperature.

Heat budget analysis shows that the seesaw-temperature distributions are resulted from different processes. For the Eurasia region, the warming (cooling) is contributed by the adiabatic heating (cooling) process induced by downward (upward) anomalies.

For the Northern Pacific region, the temperature variation is mainly due to zonal advection associated with interannual zonal wind anomalies acting on the climatological temperature gradient. For the cooling over the Northern Pacific, the cold advection is due to strong easterly anomaly in the box, which is associated with a pair of cyclonic gyres flanking the equator in upper troposphere. Further analysis shows that the upper-level cyclonic gyres are due to the Gill response to La Niña-like SST anomalies over the equatorial eastern Pacific. The vice is versa for the warming in the Northern Pacific region. Numerical experiments with an AGCM also prove this relationship.

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Table captions

Table 1 Selected years for composite, which is based on the standardized time series of PC2. The positive- (negative-) index years denotes those years with values beyond 1 (-1).

Figure captions

Fig. 1 The first two leading modes ($\times 0.01$) and corresponding normalized principal components of EOF analysis applied to the summer (June to August, JJA) mean temperature anomalies averaged over 500 - 200 hPa: (a) EOF1, (b) PC1, (c) EOF2, (d) PC2. The percent variance is marked on top right of panel (a) and (c). Rectangles in (c) denote East Asian region (30°N-50°N, 60°E-120°E) and the Northern Pacific region (20°N-40°N, 180°-120°W), which are focused on in this study.

Fig. 2 The total variance (%) explained by each of the first five EOF modes. Error bars are determined by the formula of North et al. (1982).

Fig. 3 Time evolution of composited monthly temperature anomalies (red, K) averaged over 500-200 hPa for the East Asian region (30°N-50°N, 60°E-120°E) and its tendency (blue, K month⁻¹).

Fig. 4 Composite of 500-200 hPa averaged temperature anomalies budget terms (K month⁻¹) for the East Asian region (30°N-50°N, 60°E-120°E) in May. From left to right, observed temperature tendency, horizontal temperature advection, adiabatic term and diabatic term.

Fig. 5 (a) Composite profiles of pressure velocity anomalies (Pa s⁻¹) averaged over the East Asian region (30°N-50°N, 60°E-120°E) in May. (b) Same as in (a), except for over the Northern Pacific region (20°N-40°N, 180°-120°W) in June.

Fig. 6 Same as in Fig. 3, except for the Northern Pacific region (20°N-40°N, 180°-120°W).

Fig. 7 (a) Composite of 500-200 hPa averaged temperature anomalies budget terms (K month^{-1}) for the Northern Pacific region (20°N - 40°N , 180° - 120°W) in June. From left to right, observed temperature tendency, horizontal temperature advection, adiabatic term and diabatic term. (b) Decomposition of horizontal advection term in (a).

Fig. 8 Composite of interannual wind perturbation (vectors, m s^{-1}) and climatological temperature (shaded, K) in June; both are vertical averaged within 500 -200 hPa. Markers “C” denote cyclonic gyres. The rectangle marks the Northern Pacific region (20°N - 40°N , 180° - 120°W).

Fig. 9 Composite of interannual wind perturbation at 850 hPa (vectors, m s^{-1}) and sea surface temperature (SST) anomaly (shaded, K) in June. Markers “A” denote anticyclonic gyres. The rectangle marks the equatorial eastern Pacific region (15°S - 10°N , 160°E - 80°W), where cold SST anomaly (-1 K) is prescribed in the sensitivity experiment.

Fig. 10 250-hPa wind response to the cold SST anomaly prescribed over the equatorial eastern Pacific region. Markers “C” denote cyclonic gyres. The rectangle marks the Northern Pacific region (20°N - 40°N , 180° - 120°W).

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415 1 (-1).

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Composited years	
Positive index years	1961, 1967, 1971, 1978, 1984, 1994, 2000, 2001
Negative index years	1958, 1969, 1981, 1983, 1987, 1992, 1993, 1995

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 478 surface temperature (SST) anomaly (shaded, K) in June. Markers “A” denote
 479 anticyclonic gyres. The rectangle marks the equatorial eastern Pacific region (15°S-
 480 10°N, 160°E-80°W), where cold SST anomaly (-1 K) is prescribed in the sensitivity
 481 experiment.

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486 Fig. 10 250-hPa wind response to the cold SST anomaly prescribed over the
 487 equatorial eastern Pacific region. Markers “C” denote cyclonic gyres. The rectangle
 488 marks the Northern Pacific region (20°N-40°N, 180°-120°W).

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