



Zonally asymmetric mode of anomalous activity in summer Asian subtropical westerly jet and its possible sources

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Abstract

The ERA-Interim (1979–2016) and National Center for Environmental Prediction (NCEP) (1958–2016) reanalysis data are applied in an empirical orthogonal function (EOF) decomposition of the summer zonal wind anomaly in the upper troposphere (at 200 hPa) over Asia. Consistent spatio-temporal modes are derived from the two datasets on different time scales, with the first three dominant modes representing the principal features of the summer Asian subtropical westerly jet (ASWJ). The first and third modes respectively describe the meridional position deviation and the overall strength variations of ASWJ, and both exhibit zonally symmetric distributions, which have been extensively investigated. The second mode describes a zonally asymmetric distribution of the jet over Asia, which reflects coordinated variations in the upstream and downstream systems and has not yet been systematically studied. In this study, we focus on the analysis of the second mode of ASWJ. The observation results show that the second mode is closely related to external forcing factors as well as the large-scale circulation at mid-high latitudes. Through the interaction of the preceding North Atlantic sea surface temperature (SST), the simultaneous soil moisture, and the atmospheric circulation that propagates zonally via the waveguide effect of the jet, the ocean–land–atmosphere coupled system can produce coordinating impacts on the variability of ASWJ. These results aid in a more complete and comprehensive understanding of the physical characteristics of the summer westerly jet and provide a new perspective for the study of the variability of ASWJ.

Keywords Asian subtropical westerly jet · Soil moisture · North Atlantic sea surface temperature · Ocean–land–atmosphere interaction

1 Introduction

The subtropical upper-tropospheric jet stream is an important component of the planetary-scale circulation and plays a vital role in the transportation and equilibration of atmospheric momentum and energy. The weather and climate in the Asia-Pacific area are significantly affected by the Asian subtropical westerly jet (ASWJ) (Cressman 1981; Li and Zhang 2014; Wang and Zhang 2015). To date, a number of studies have investigated the variation of ASWJ on different timescales and the associated mechanisms. As for the seasonal variation, ASWJ is a crucial part of the East Asian summer monsoon system, its north–south variation is an important signature of the seasonal transformation in the atmospheric circulation and directly affects the progression of monsoons, the position of the eastern rain belt, and the times at which Meiyu period begins and ends (Lin and Lu 2008; Sampe and Xie 2010; Huang et al. 2012). As for the interannual variation, the meridional change in the position of ASWJ usually directly

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corresponds to the summer rainfall anomaly over East Asia, which interacts with circulation systems at different latitudes through the condensation latent heat feedback and the meridional teleconnection (Lau et al. 2000; Lu 2004; Li et al. 2010; Lin et al. 2010). The strength of ASWJ is related to the secondary circulation anomaly, which has an influence on weather and climate in the Asia-Pacific region (Wu and Wang 2002; Wang et al. 2010; Liu et al. 2012; Wu et al. 2016; Wu and Wu 2019). Some studies have also indicated that the summer ASWJ exhibits significant interdecadal variations (Yu and Zhou 2007; Kwon et al. 2007; Zhang and Huang 2011).

In general, current studies on ASWJ focus on the displacement of its position and the variations in its strength. The anomalous activity of ASWJ is characterized primarily by the meridional displacement and secondarily by the intensity variation (Lin and Lu 2005), and the position of the summer jet generally exhibits consistent variations with the movement of the East Asian rain belt. Therefore, much attention has been paid to the north–south movement of the ASWJ and its physical causes. As an important external forcing factor that affects the atmospheric general circulation, the tropical sea surface temperature (SST) makes a significant contribution to the jet's south–north oscillation. The studies of Wang et al. (2000) and Lin et al. (2010) revealed a correlation between preceding and simultaneous mid-eastern Pacific SST anomalies and the meridional variation of the ASWJ. The study of Qu and Huang (2012) indicated that the SST anomalies in the tropical Indian Ocean can cause south–north displacement of the ASWJ by exciting eastward-propagating Kelvin waves. Kuang and Zhang (2006) suggested that the meridional position of the ASWJ is also related to the surface sensible heating over the Arabian Sea and north of the Indian Peninsula. The numerical results of Du et al. (2016) showed that the meridional displacement of the ASWJ can be attributed to the combined effect of the SST in the tropical mid-eastern Pacific Ocean, the Indian Ocean, and the Northwestern Pacific Ocean. In addition, the convective activity in the Northwestern Pacific Ocean is significantly affected by the mid-eastern Pacific SST and the Indian Ocean SST (Lin and Lu 2009; Xie et al. 2009). Kosaka and Nakamura (2010) and Surendran et al. (2018) suggested that the tropical SST anomalies affect the convective activity in the Northwest Pacific Ocean, thereby impacting on the displacement in the positions of the atmospheric meridional circulation and the ASWJ.

In this study, by decomposing the zonal wind anomaly at 200 hPa during summer (June through August) using empirical orthogonal function (EOF), we find that there is a stable zonally asymmetric mode of jet stream variation beyond our general understanding in the past. Some studies examined the ASWJ and derived distributions that are similar to which described in this paper (Du et al. 2016). This mode represents one important form of significant change in ASWJ and is considerable for knowing the correlation between the

upstream and downstream systems of the Asian jet (Yang et al. 2004; Zhao et al. 2014). However, in these researches, there is a lack of in-depth investigation of the physical characteristics of the zonally asymmetric mode of the ASWJ and the relevant mechanism, which limited our understanding in these aspects.

Based on these considerations, the current study focuses on discussing the characteristics of the ASWJ activity corresponding to the zonally asymmetric mode and its possible causes. In contrast to the previous analyses, our results indicate that the tropical SST is not the key factor that causes variations in the zonally asymmetric pattern of ASWJ. The asymmetric mode that is closely related to the thermodynamic signal of the underlying surface mainly originates from the upstream mid-high latitude regions. An analysis of the external oceanic and continental forcing factors reveals a seasonal-scale correlation between them. In addition to the influence of the thermal forcing, the impact of internal atmospheric processes on the zonally asymmetric distribution of the ASWJ is also considered, and the results confirm that the configurations of the upstream and downstream systems are closely related to adjustments in the large-scale circulation. In this paper, we investigated in detail the physical factors leading to the significant change in the zonally asymmetric mode of the jet and analyzed the possible physical processes. This provides a new perspective that enables us to better understand the summer ASWJ.

2 Data and methods

The data used in this study include the monthly wind field, the geopotential height field, the temperature field, and the surface soil moisture field reanalysis data from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-Interim (1979–2016) and the United States National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (1958–2016), with a horizontal resolution of $2.5^{\circ} \times 2.5^{\circ}$. Some studies have confirmed that the ERA-Interim data are more reliable and can better represent the climate variables in Eurasia than the NCEP data (Mooney et al. 2011; Decker et al. 2012); however, the ERA-Interim dataset is of the relatively short time period, starting in 1979. To improve the reliability of the results and investigate the variations of the jet on a relatively long timescale, we use both datasets for comparison and analysis.

In addition, in our discussion of the quasi-stationary wave activity linked to the summer zonal wave train in Eurasia, we used the three-dimensional wave activity flux (the T–N flux) defined by Takaya and Nakamura (2001). The calculation of T–N flux is as follows:

$$W = \frac{p}{2|U|} \left(\begin{array}{l} U(\psi'_x{}^2 - \psi'\psi'_{xx}) + V(\psi'_x\psi'_y - \psi'\psi'_{xy}) \\ U(\psi'_x\psi'_y - \psi'\psi'_{xy}) + V(\psi'_y{}^2 - \psi'\psi'_{yy}) \\ \frac{f^2}{N^2} [U(\psi'_x\psi'_z - \psi'\psi'_{xz}) + V(\psi'_y\psi'_z - \psi'\psi'_{yz})] \end{array} \right),$$

where $|U|$ is the horizontal wind speed, U and V are the summer average zonal and meridional wind speeds, respectively; ψ' is the anomaly in the summer stream function, p is the pressure, f is the Coriolis parameter, and N^2 is the static stability. As a measure of the wave energy propagation, the horizontal component of the T–N flux represents the direction and magnitude of the horizontal propagation of wave energy. The calculation method does not require that the basic flow field is the zonal average air flow but can include the zonal non-uniform meridional and zonal winds. Therefore, this method is highly suitable for describing non-flat background circulations in the mid-high latitude regions.

3 Multi-modal characteristics of the summer ASWJ

The subtropical westerly jet is a planetary-scale circulation system that persists in the upper troposphere. In traditional weather and climate analyses, the westerly zone with the zonal wind speed greater than 30 m/s at 200 hPa is generally defined as the jet. The wind speed at the center (the jet core) refers to the jet strength, and the long axis of the jet zone is the jet axis. Due to the impact of unique terrain and land–sea distribution in Asia, the atmospheric circulation and meteorological factors in this region exhibit significant seasonal variations: the ASWJ is strongest in winter, when its center is above Japan (near 30° N), and its strength can reach 70 m/s; whereas it is weakest in summer, when the jet's center apparently moves northward with significantly decreased wind speed. Three maxima of westerly winds are distributed along 40° N, i.e., over the Caspian Sea, on the northern side of the Tibetan Plateau, and above the Northwestern Pacific Ocean, respectively, among which the strongest jet zone is located on the north of the plateau with a strength of approximately 30 m/s (Berggren et al. 1958; Yeh et al. 1959; Ren et al. 2010). In addition, according to the distribution of the standard deviation of the summer upper-tropospheric zonal wind (not shown), the active centers of the jet are located south and north of the Asian jet axis respectively, which indicates that the ASWJ's variations feature a meridional displacement and inclination along its axis.

3.1 Main spatio-temporal modes of the ASWJ

To reveal the main characteristics of the anomalous activity of summer ASWJ, we adopt two sets of reanalysis data in EOF decomposition of the raw zonal wind anomaly in the upper troposphere (at 200 hPa) over Asia (20–60° N, 40–160° E). Area weighting is accomplished by multiplying the zonal wind field by the square root of cosine of latitude to ensure equal areas are afforded equal weight (Sun et al. 2013). To determine whether the main modes of the ASWJ change during different periods of time, we use the ERA-Interim data for the period from 1979 to 2016 and the NCEP data for the period from 1958 to 2016 for comparison, and derive the first three modes that reflect the jet anomaly (Fig. 1). The results indicate that the data with different time span give relatively consistent spatial patterns, and their temporal coefficients also exhibit similar variations (the correlations corresponding to the same time periods in two datasets of the three modes are 0.96, 0.95, and 0.96). Further analysis indicates that the variance contribution ratios of the first three modes to the total variance of the ASWJ corresponding to the ERA-Interim and NCEP datasets are 23.5%, 17.0%, 13.3% and 23.8%, 15.7%, 11.2%, respectively. Therefore, these three modes can indeed reflect the main features of the variability of the summer ASWJ and are not affected by the data used or the length of time. All the results in this article are compared with two datasets. Since the results are generally consistent, only the figures of the ERA-Interim data are shown in the following text except for Fig. 1.

As shown in Fig. 1, the first mode of the jet exhibits anomalous variation in the zonal wind that is opposite in the south and north to 40° N in the spatial field. Since the axis of the summer subtropical jet is usually located at near 40° N, it reflects the meridional movement of the ASWJ. This variation represents the north–the south movement of the jet that is quasi-parallel to the jet's axis and exhibits consistent extension in the east–west direction. From the perspective of the temporal coefficient corresponding to this mode, the meridional displacement of the jet has 2–4-year and 6-year interannual oscillations and an interdecadal southward movement since the 1980s (the wavelet spectrum figure is omitted). The spatial field of the second mode exhibits a quadrupole distribution over Asia and shows an inclination in the southwest–northeast axial direction. In contrast to the consistent zonal variations of the first mode, the second mode exhibits zonally asymmetric variations of the jet over East and West Asia, which to some extent reflects the coordinated effect of the upstream and downstream systems. In addition to the interannual variations of 2–4 years and 8 years, the temporal coefficient of this mode also exhibits evident interdecadal changes, with a negative phase from the 1970s to mid-1990s, and a positive phase during the periods before and after that. The center of the positive anomaly of the third mode is located zonally

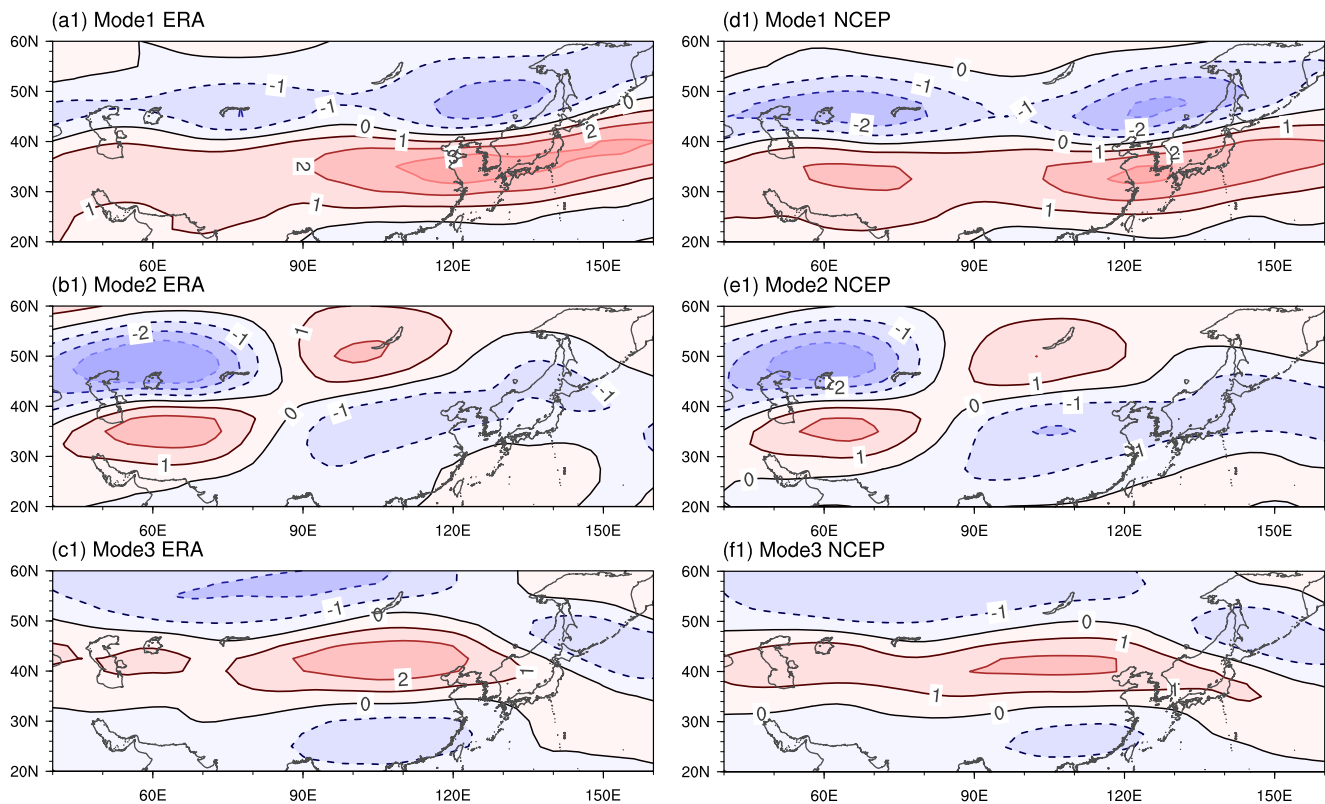


Fig. 1 The first three leading EOF mode patterns [m s^{-1}] (a1–f1) and corresponding PC time series (a2–f2, solid and dashed lines denote 7-point moving average and linear tendency, respectively) for the summer

200 hPa zonal wind anomaly, derived from both ERA-Interim (a1–c1, a2–c2) and NCEP (d1–f1, d2–f2) reanalysis data

symmetrically near 40°N and reflects the overall change in the strength of the ASWJ with the 2–3-year interannual variation; its interdecadal characteristics are not significant.

The characteristics of the zonally symmetry of the ASWJ have been widely investigated in previous studies. To further understand its zonally asymmetric variations, we normalize the time sequence corresponding to the second mode (PC2) and select anomalous years with the absolute value greater than one standard deviation (1σ) for the composite analysis. By comparing the composited distribution of the ASWJ (Fig. 2), we found that the jet is generally weak with a relative straight axis during the positive anomalous years; while it obviously strengthens and extends significantly in the east–west direction in the negative anomalous years. In particular, the variation in the strength of upstream West Asian jet is evident, and the jet axis also presents an anomalous inclination in the northwest–southeast direction. Consequently, the second mode plays an indispensable role in the variability of the ASWJ. As a result of its zonally asymmetric structure, there are obvious changes in the jet’s central position, the area and strength of the upstream and downstream, accompanied by inclination and rotation of the jet axis. Therefore, it would be incomplete to investigate the jet’s variability only from the perspective of changes in its position and strength. An intensive study of the mode is crucial for a comprehensive

understanding of the ASWJ variation and the circulation that connects the upstream and downstream. Currently, few researches have been conducted on the asymmetric mode, and our cognition in this subject is still limited. Therefore, the following discussion focuses on analyzing the physical characteristics and possible sources of the zonally asymmetric mode of ASWJ.

3.2 Physical characteristics of the zonally asymmetric mode

Figure 3 shows the composited differences of 200 hPa zonal wind anomaly, 200-hPa geopotential height anomaly, 200–850-hPa tropospheric thickness anomaly, and 200–500-hPa averaged meridional temperature gradient anomaly between positive and negative anomalous years of the jet’s second mode, which reflect the configuration among the upper-level wind/pressure fields, the thermodynamics of the troposphere and the mid- and upper-level meridional temperature gradient related to the anomalous ASWJ activity. Figure 3a describe the distribution of the composited 200-hPa zonal wind field anomaly derived from two reanalysis datasets. Similar to that of the second mode shown in Fig. 1, the spatial distribution of the jet anomaly exhibits a horizontal zonally asymmetric pattern that is inclined in the southwest–northeast direction. In

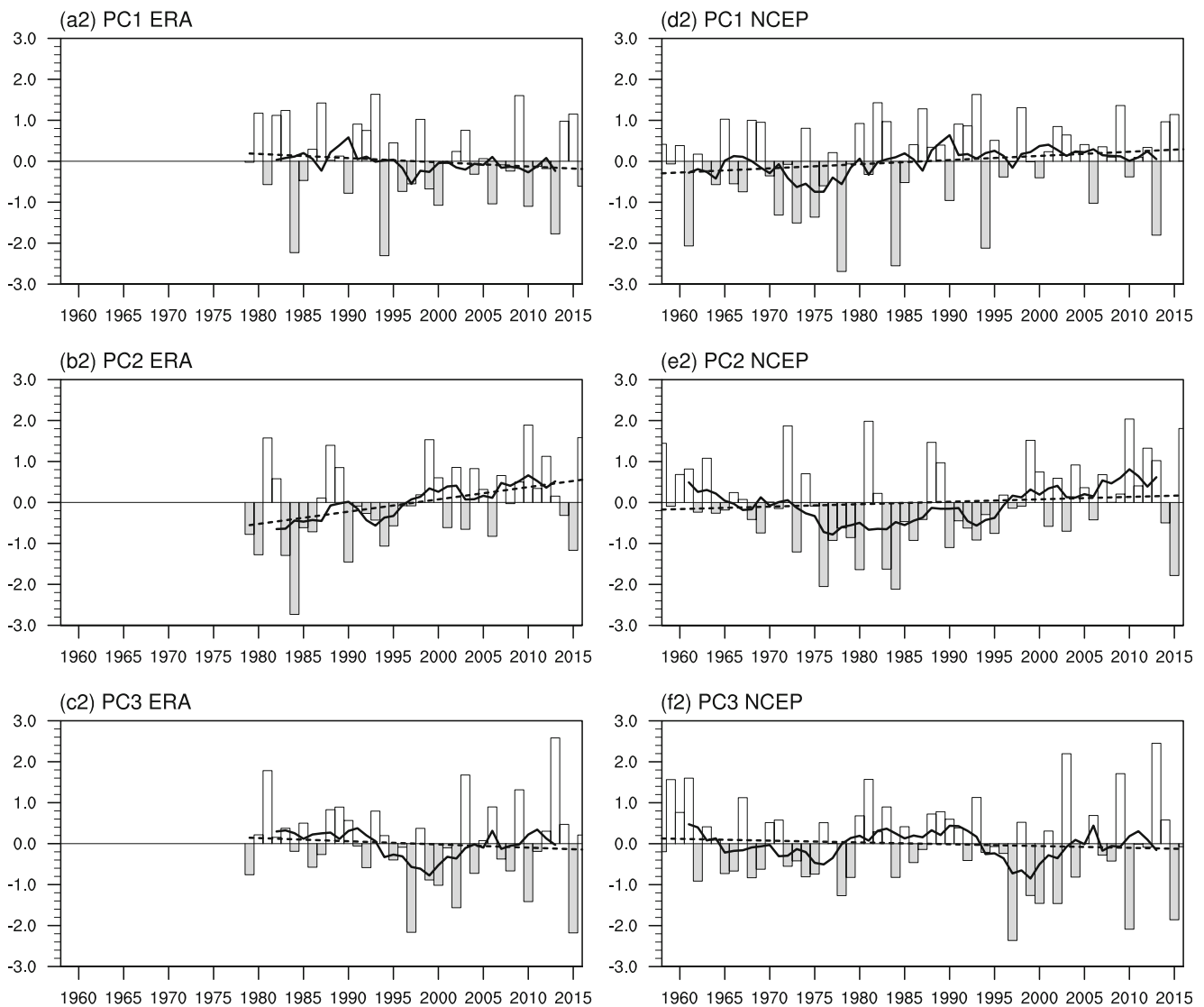


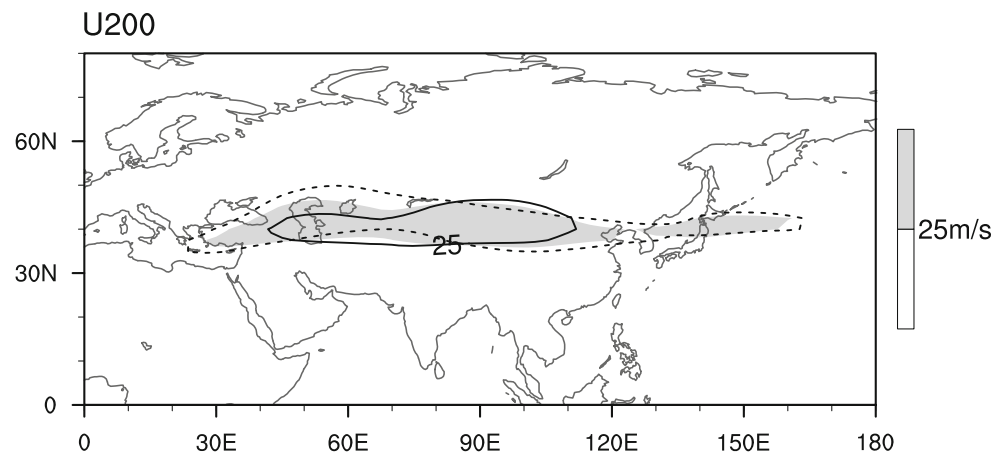
Fig. 1 (continued)

particular, the anomaly has two positive centers, located near Iran and over the Lake Baikal and two negative centers, located over Kazakhstan and eastern China. The four centers of anomalous activity appear to the north and south of the jet axis in East and West Asia, respectively. Consistent with the wind field anomaly, the composited upper-level geopotential height anomaly (Fig. 3b) is generally featured by a zonal wave train that propagates along the jet at 40° N. The areas above East Asia and West Asia correspond to positive and negative anomalies in the geopotential height, respectively, and this signal propagates from upstream mid- and high-altitude regions and extends from west to east. In addition, the distributions of the lower-level zonal wind and the geopotential height are highly similar to that of the upper-level horizontal structure, and the magnitude increases with increasing altitude (not shown). These results indicate that this anomalous jet structure is quasi-barotropic and that the upper-level wind and pressure

fields dominate the distribution of the circulation throughout the whole atmospheric layer. Figure 3c show the composited 200–850-hPa tropospheric thickness field, which represents the horizontal thermodynamic structure of the troposphere, and the distribution of its anomaly is consistent with that of the geopotential height anomaly. The anomalous positive and negative centers correspond to its warming and cooling centers, respectively. In addition, the temperature and pressure fields exhibit the aforementioned stable configuration throughout the troposphere, indicating the quasi-barotropic structure of the vertical circulation field.

According to the thermal wind theorem, the variation in the zonal wind with altitude is proportional to the north–south temperature gradient; the positive center of upper-level zonal wind is usually located above the high-value region of the meridional temperature gradient. Because the lower troposphere is significantly affected by the local underlying surface,

Fig. 2 The composited summer Asian subtropical westerly jet [m s^{-1}] for PC2. Solid and dashed lines denote the composited results of positive and negative anomalous years. Shading indicates the average value



the general circulation is not geostrophically balanced. Therefore, we select the meridional temperature gradient at the middle and upper troposphere to investigate the relationship between the ASWJ and the atmosphere's thermodynamic anomaly. The average temperatures of the middle and upper levels generally reflect the overall variation in the temperature of the troposphere, which has been adopted in many studies (Kuang and Zhang 2006; Yu and Zhou 2007). According to the work of previous, we define the meridional temperature gradient as the difference between the temperature on the north and south sides of adjacent zonal belts. A positive (negative) value corresponds to warming in the south (north), cooling in the north (south), and an increase (a decrease) of the westerly wind with altitude. By comparing the composited field of the meridional temperature gradient shown in Fig. 3d and the composited field of the zonal wind shown in Fig. 3a, it is evident that the anomalous distribution of the ASWJ is significantly affected by the meridional temperature gradient in the troposphere, which complies with the thermal wind theorem. Therefore, the variation in the upper-level wind field is closely related to the atmospheric thermodynamic anomaly. On this basis, the physical causes of the jet are investigated and discussed in the next section.

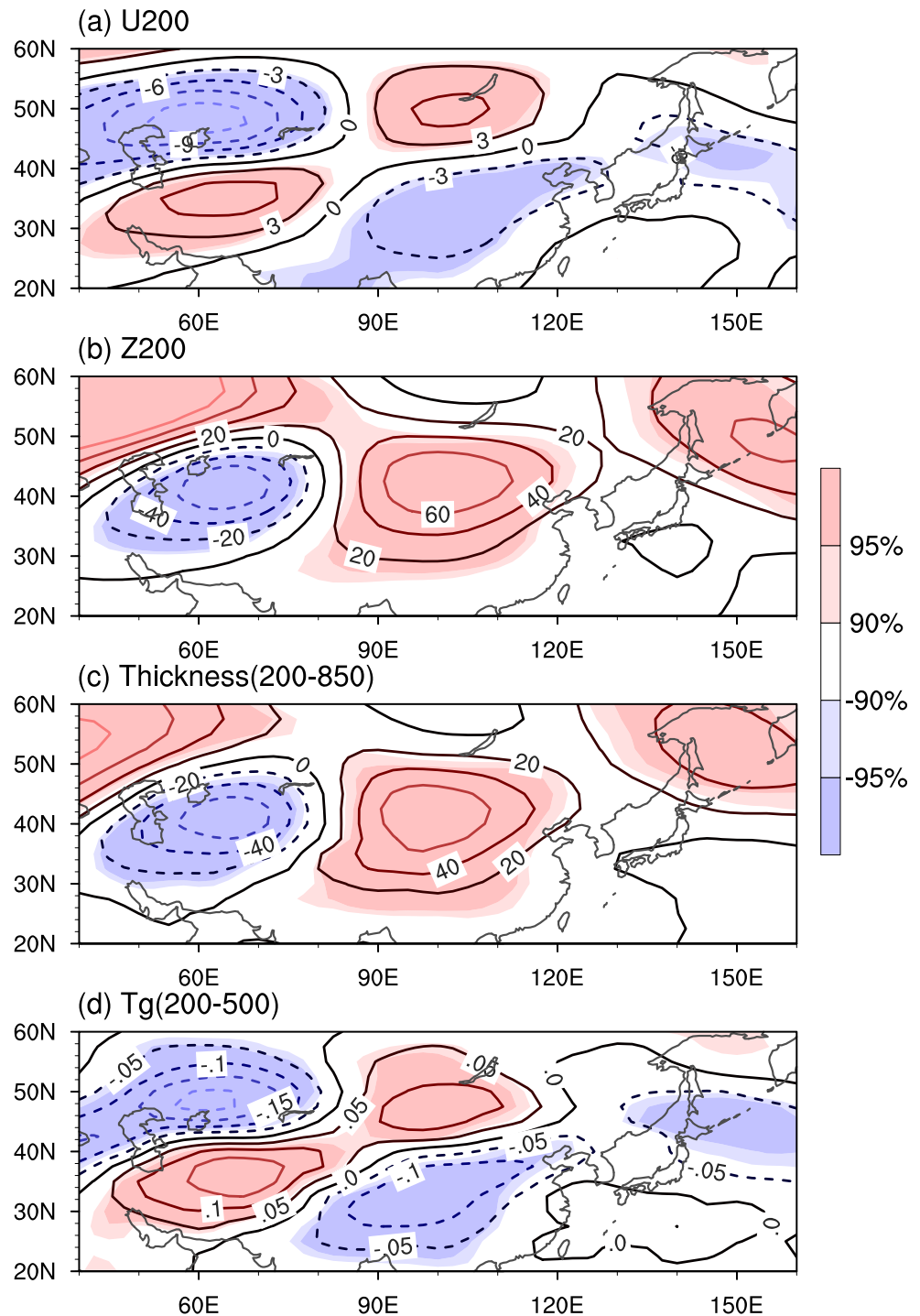
4 Possible sources for the variability in the zonally asymmetric mode of the summer ASWJ

Studies on the mechanisms accounting for the variations of ASWJ mainly focus on the impact of external forcing and atmospheric internal processes. As mentioned above, the tropical SST anomalies have a very important impact on the jet's variation: the preceding mid-eastern Pacific SST (Lin and Lu 2009; Du et al. 2016) and the simultaneous Indian Ocean SST (Qu and Huang 2012) can both impact the position of the ASWJ significantly. Moreover, the thermodynamic and dynamic effects of the Tibetan Plateau and the Eurasian snow

anomaly are also considered as important factors leading to variations in the Asian jet (Walland and Simmonds 1996; Clark and Serreze 2000; Wu et al. 2010, 2012b). In addition to the impact of external forcing factors, that of internal atmospheric adjustment is considerable. Atmospheric internal processes are usually of two types: large-scale circulations and transient disturbances. Herein, we mainly consider the impact of large-scale circulation (zonal and meridional teleconnection) on the ASWJ. Nitta (1987) proposed that the East Asia-Pacific wave train (EAP/PJ wave train) is the meridional teleconnection pattern that causes a significant variation in the north–south position of the jet. While the Asian jet is the atmospheric waveguide in the upper troposphere in the mid-latitude region, which has strong interaction with the large-scale zonal circulation (Qu et al. 2017). Lu et al. (2002) proposed for the first time that there exists an evident teleconnection pattern in the jet from North Africa to East Asia in the upper troposphere during summer; Enomoto et al. (2003) identified this teleconnection as the “Silk Road” pattern. Subsequent studies indicated that it is the representation of a Northern Hemisphere circumglobal teleconnection (CGT) in Eurasia (Lau et al. 2004; Ding and Wang 2005; Ding et al. 2011).

In this study, we focus on analyzing the zonally asymmetric mode of the summer ASWJ variability. It exhibits a quadrupole horizontal structure over Asia, which reflects the characteristics of the anomalous variation of the summer jet with a southwest–northeast inclination, and there is a close correlation between the anomalous distribution pattern of the ASWJ and the configuration of the upstream and downstream systems. Currently, the mechanism for the formation of this anomalous mode is still far from understood. The studies of Du et al. (2016) preliminarily investigated the possible physical mechanism for the formation of ASWJ anomalous modes from the perspective of the SST anomalies and emphasized the contribution of the Pacific SST to the second mode. It should be noted that

Fig. 3 The composited differences of 200 hPa zonal wind anomaly [m s^{-1}] (a), 200 hPa geopotential height anomaly [gpm] (b), 200–850 hPa tropospheric thickness anomaly [gpm] (c), and 200–500 hPa averaged meridional temperature gradient anomaly [K°N] (d) for PC2. The 95% (90%) confidence levels are dark (light) shaded



their studies showed a close connection between the SSTs of tropical and Northwest Pacific and meridional displacement of the jet by using the singular-value decomposition (SVD) but could not derive the zonally asymmetric distribution mode of the ASWJ. Therefore, the SSTs in those regions are most likely not the dominant factors that affect the asymmetric mode of the ASWJ. Through further analysis, we found that the jet's zonally asymmetric mode is closely related to the

underlying surface thermal signal, which mainly derives from the continent and ocean in the upstream mid-high latitude regions. In particular, the signal of summer land surface anomaly is distinct. In the following sections, we focused on the impact of external forcing (e.g., soil moisture and North Atlantic SST) and the atmospheric internal processes on the zonally asymmetric mode of the ASWJ through observational analysis and investigated possible physical mechanisms.

4.1 Relationship with external forcing factors

Figure 4 shows the correlation between the PC2 and the simultaneous summer upper layer surface soil moisture anomaly. It can be seen that there is a close relationship between variations in the second mode of the ASWJ and summer surface soil moisture, which is significant at the 0.05 level in the vast mid-high latitude regions over Eurasia. A significant positive correlation is located near the Lake Balkhash and north of the Lake Baikal, and significant negative correlations occur over Europe and south of the Lake Baikal. Such a spatial pattern is similar to that shown in Fig. 3b, c, which indicates that there is a relatively good correspondence between the surface soil moisture anomaly and the spatial distributions of the atmospheric circulation and the thermodynamic anomaly related to the second mode. To some extent, this result reflects the effect of land–atmosphere coupling over Eurasia during summer: the tropospheric warm anomaly corresponds to dry anomaly of the surface soil; in contrast, the tropospheric cold anomaly corresponds to the wet anomaly of the surface soil.

In fact, soil moisture has the ability to remember the dry–wet anomalies; the anomaly duration from week to month can even reach the seasonal scale. Besides, the relationship between soil moisture and evapotranspiration is a key physical process between the land–atmosphere interface (Koster and Suarez 2001; Lorenz et al. 2010; Seneviratne et al. 2010; Zhang and Zuo 2011; Orth and Seneviratne 2012). The relatively dry soil in summer results in relatively high atmospheric temperature above this region due to the evaporation feedback mechanism; in turn, the increase in temperature increases the evaporation of soil moisture, and the drier soil further enhances the atmospheric temperature and vice versa. Such an interaction is present as a positive feedback loop, and the land surface soil moisture anomaly enables the thermodynamic anomaly of the overlying atmosphere to be maintained.

Figure 5 displays the correlation between PC2 and the North Atlantic SST anomalies of the preceding winter. As shown in the figure, the connection between the two exhibits

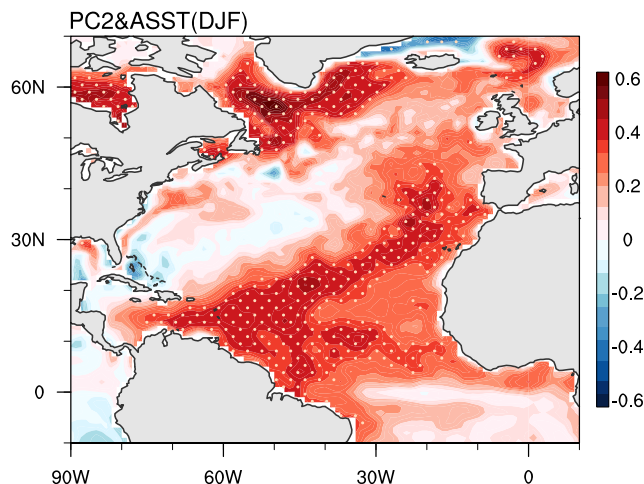
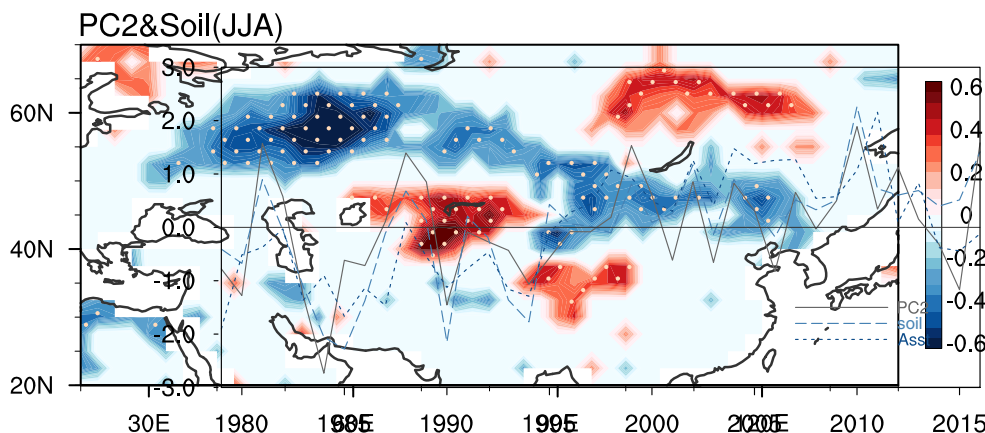


Fig. 5 As in Fig. 4, but for the North Atlantic SST anomalies of preceding winter

like a tri-pole pattern. The correlation is weak in the eastern sea area of the USA near 30° N and significant positive on its north and south sides. In addition, the correlation with the spring and summer Atlantic SSTs exhibits similar spatial patterns but is relatively weak to winter. In previous researches of the physical mechanism of ASWJ variations, the forcing of tropical SST was given more consideration. The findings of this study indicate that the SST forcing of the upstream mid-high latitudes contributes significantly to the jet’s zonal asymmetric structure. In our early work (Li and Chen 2017), the atmospheric general circulation model NCAR CAM5 was used to compare the relative contribution of SST anomalies of the North Atlantic Ocean, Indian Ocean, and the Northwest Pacific Ocean to the second mode of the ASWJ. It turned out that the Indian and the Northwest Pacific SST anomalies have more significant effects on the jet stream over East Asia and the Pacific Ocean, but the quadrupole distribution of zonal asymmetric mode cannot be simulated; while the North Atlantic SST anomalies are closely related to the jet distribution in West Asia, which can well describe the energy transfer of the upstream area and simulate the quadrupole pattern.

Fig. 4 Correlation between PC2 and simultaneous summer upper layer soil moisture anomalies. Dots indicate significant at the 95% confidence level



To have a better understanding of the relation between these two factors and the ASWJ, we select the grids with correlation coefficients that are significant at the 0.05 level to calculate the regional average of the summer surface soil moisture in Eurasia and the preceding winter North Atlantic SST, and subtracted the sum of data in negative-value regions from that in positive-value regions. By normalizing, we derive the summer soil moisture index and the preceding winter North Atlantic SST index (Fig. 6). As shown in the figure, they have good correspondences with the variation of PC2, and all three indexes reveal the increasing trends. Correlation coefficients between PC2 and the summer soil moisture index/the preceding winter North Atlantic SST index before and after removing the trend are 0.78/0.5 and 0.77/0.39, respectively (Table 1). Both are significant at the 0.05 level, which means that the relationship between PC2 and soil moisture index is more reflected in the interannual contact, while the relationship with Atlantic SST is partly influenced by the interdecadal growth trend.

Figure 7 shows the circulation and the thermodynamic anomaly field derived from the regression of these two indexes. Comparing the results with Fig. 3, the wind-pressure fields and locations of anomalous activity centers retrieved from the summer soil moisture index and the preceding winter North Atlantic SST index are generally consistent with those of the second jet mode. The horizontal structure of the upper-level wind field (Fig. 7a, e) exhibits an obvious zonally asymmetric quadrupole distribution with positive and negative centers located over Kazakhstan, Iran, Lake Baikal, and east of China. The composited geopotential height field (Fig. 7b, f) also shows a wave train pattern that propagates zonally along the upper-level jet. The areas above East and West Asia correspond to positive and negative anomalies in the geopotential height, respectively. And the wave signal, originating from the upstream mid-high latitude regions, propagates from west to east. However, the circulation and the thermodynamic field retrieved from the North Atlantic SST index are relatively weak compared with those retrieved from the soil moisture index. Therefore, the simultaneous soil moisture and the

preceding winter North Atlantic SST play significant roles in the variability of the zonal asymmetric mode of the ASWJ. In particular, the summer land surface feedback is nonnegligible.

4.2 Relationship with atmospheric internal processes

In addition to the impact of external forcing, the internal atmospheric processes have always been considered important to the jet's variability. In summer, a zonal wave train propagates around the Northern Hemisphere along the subtropical westerly jet in the upper troposphere and forms the circumglobal circulation teleconnection. The part of circulation anomaly in Eurasian is called the "Silk Road" teleconnection pattern, which is a large-scale zonal circulation with a significant impact on the summer climate of this region. The studies conducted by Lu et al. (2002) and Chen et al. (2013) defined the temporal coefficient of the first mode in the EOF decomposition of the 200 hPa meridional wind field anomaly over Eurasia (30°–60° N, 30°–130° E) as the "Silk Road" teleconnection index. Calculation results show that the correlation coefficient between this teleconnection index and PC2 is as high as -0.75 , which also indicates that there is a close relationship between the zonal circulation anomaly and the second mode. Figure 8 shows the 200 hPa geopotential height anomaly that results from a linear regression of PC2 and the "Silk Road" teleconnection index. Both delineate the zonal Rossby wave train that propagates along the jet at 40° N in the upper troposphere, and the main activity centers are located over Europe, the Caspian Sea, Mongolia, and the coast of East Asia.

To further understand the correlation between the second mode and the zonal Rossby wave activity, Fig. 9 shows the composited difference between the 200 hPa stationary wave activity flux (the T–N flux) and relative vorticity anomaly during the PC2's positive and negative anomalous years. It can be seen that the Rossby wave train related to the second mode originates in the upper troposphere above the North

Fig. 6 Time series of PC2, the summer soil moisture index, and the preceding winter North Atlantic SST index

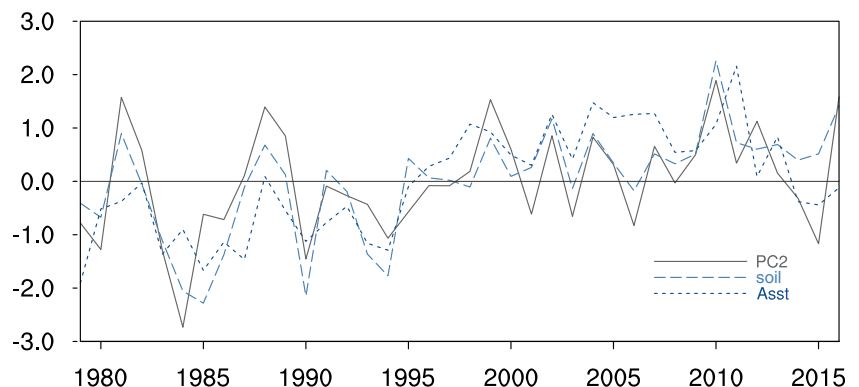


Table 1 Correlation coefficient of PC2, the summer soil moisture index and the preceding winter North Atlantic SST index

	PC2 & soil moisture	PC2 & ASST(DJF)	ASST(DJF) & soil moisture
Correlation coefficient (detrended)	0.78 (0.77)	0.50 (0.39)	0.67 (0.47)

Atlantic, passes above Europe and the Caspian Sea, and extends towards East Asia; accordingly, the T–N flux propagates the energy to downstream regions accompanying the zonal wave train, and the strongest wave activity flux is located near the Caspian Sea. However, we noted that a lower-level T–N flux cannot represent the transfer of energy in a northwest–southeast direction from Europe to East Asia (not shown), which may be related to the waveguide effect on the stationary Rossby waves. The wave trains are locked into the ASWJ, and therefore, the energy in the waves can be transferred to a further downstream region. In addition, the lower-level wave activity flux converges in the region between the North Atlantic and Europe, where can be considered as the origin

of the wave energy. These results confirm that there is indeed a correlation between the upstream and downstream systems of the Asian jet: the upstream western Asian jet is in coordinated variation with the downstream eastern Asian jet due to the impact of large-scale waves, which forms the pattern of zonally asymmetric variations.

It should be noted that previous studies have indicated that the formation of the “Silk Road” teleconnection circulation anomaly has two main mechanisms. One point of view is that its source is located in the region between the Mediterranean Sea and the Caspian Sea and formed mainly by the internal energy transformation of the atmosphere (Kosaka et al. 2009; Chen et al. 2013); the other possible mechanism is that it is

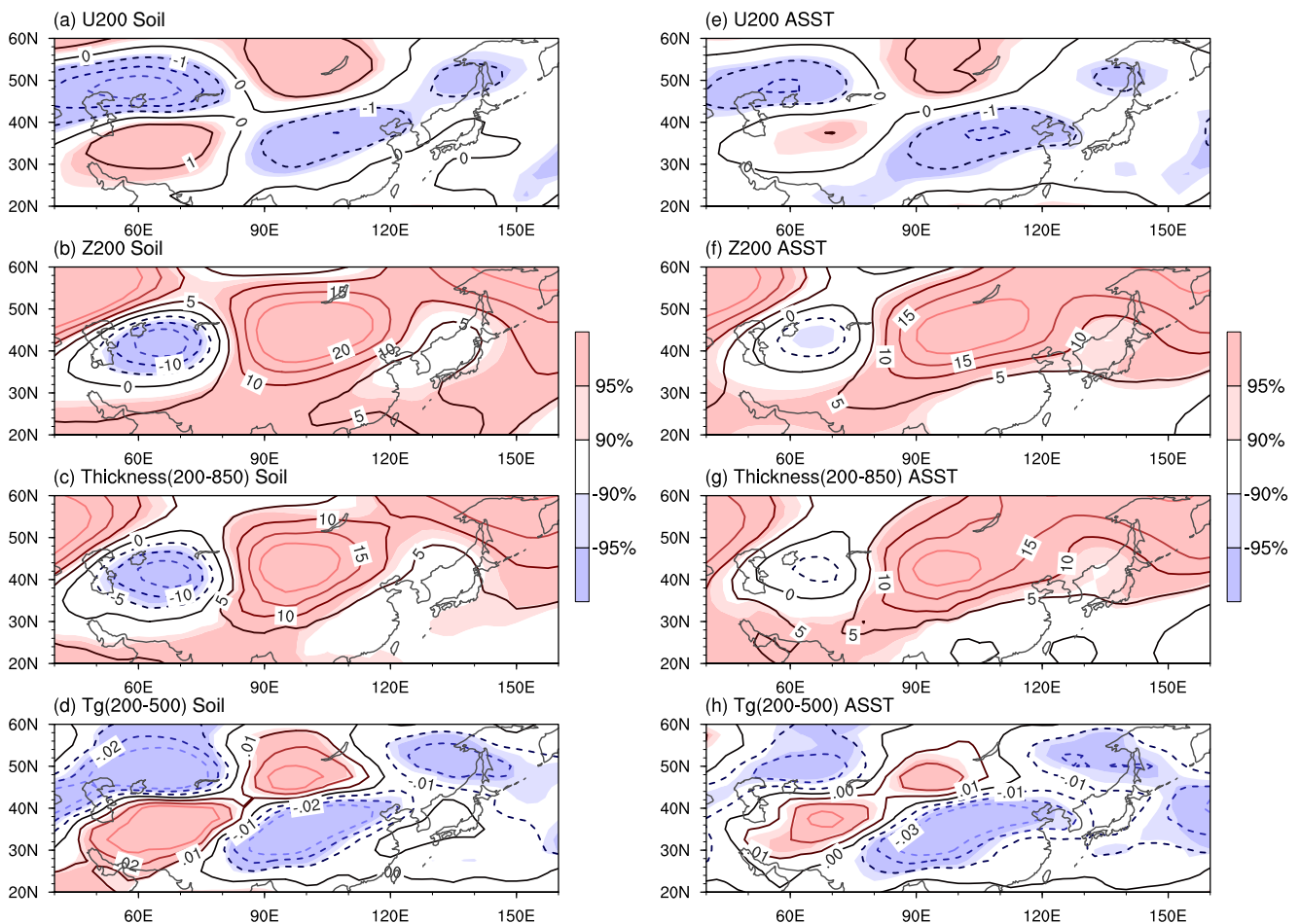


Fig. 7 Regression of 200-hPa zonal wind anomaly [m s^{-1}], 200-hPa geopotential height anomaly [gpm], 200–850-hPa tropospheric thickness anomaly [gpm], and 200–500-hPa averaged meridional temperature gradient anomaly [$\text{K}/^{\circ}\text{N}$] onto the indexes of simultaneous summer upper

layer soil moisture (a–d) and preceding winter north Atlantic sea surface temperature (e–h), respectively. The 95% (90%) confidence levels are dark (light) shaded

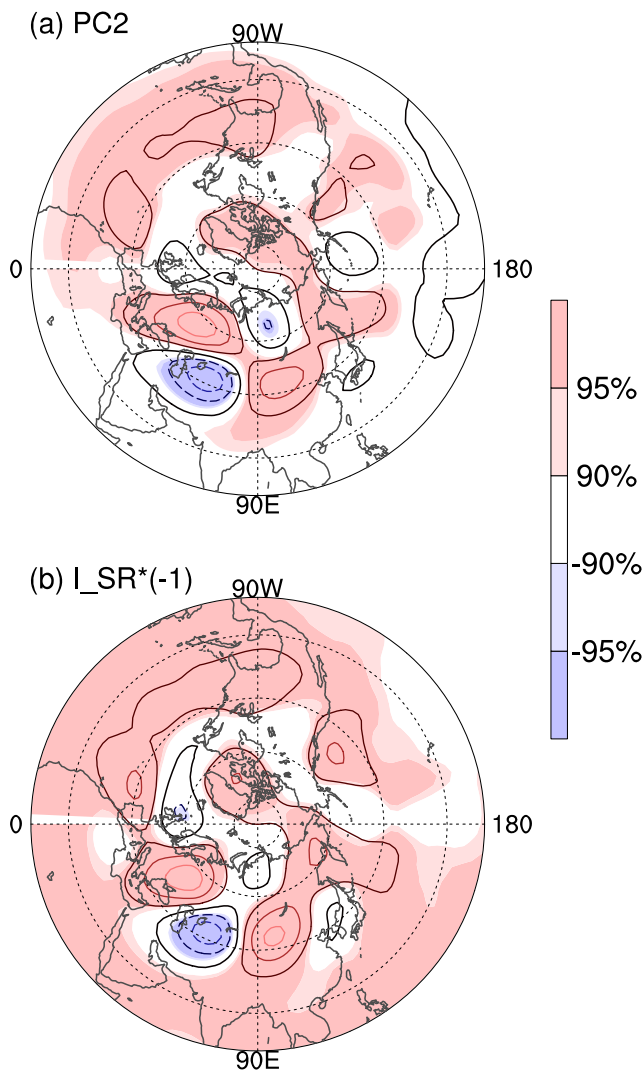
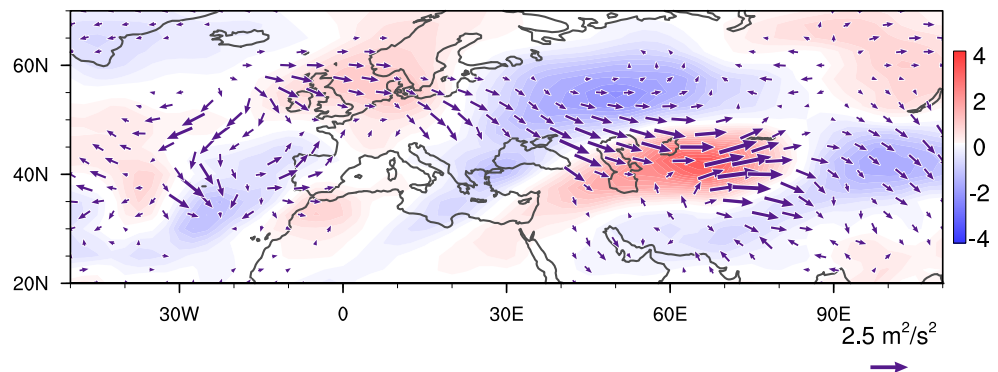


Fig. 8 Regression of 200-hPa geopotential height anomaly onto PC2 (a) and the “Silk Road” teleconnection index (b), respectively. The 95% (90%) confidence levels are dark (light) shaded

mainly related to the wave activity triggered by the heat source anomaly in association with Indian monsoon rainfall (Ding and Wang 2007; Ding et al. 2011). However, the numerical experiment of Yasui and Watanabe (2010) found that the

Fig. 9 The composited differences of 200-hPa stationary wave activity flux [$\text{m}^2 \text{s}^{-2}$] (vectors) and relative vorticity anomalies [10^{-5}s^{-1}] (shading) for PC2



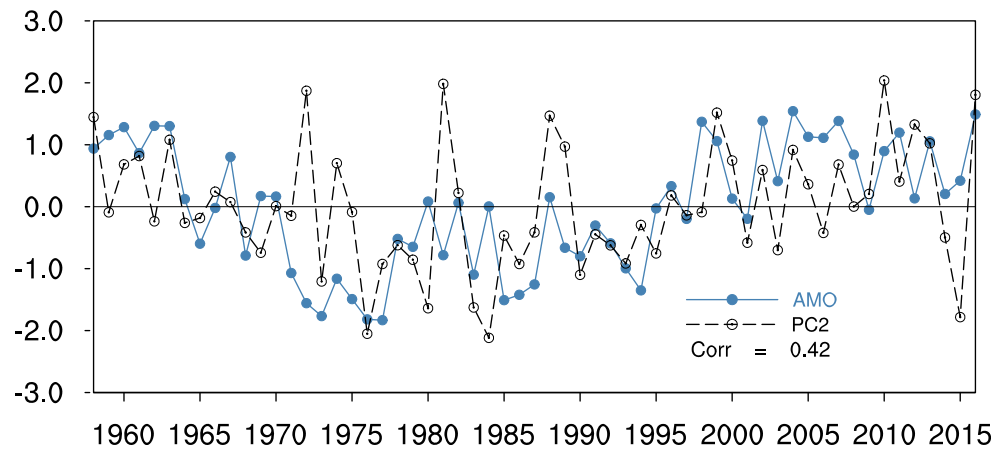
contribution of the Indian monsoon to this teleconnection pattern is very minor, and the maximum disturbance related to its formation may be located primarily in the area near the Caspian Sea. Similar to the “Silk Road” pattern, the horizontal wave activity flux that corresponds to the ASWJ second mode also exhibits its largest disturbance near the Caspian Sea (Fig. 9). However, based on this analysis, the origin of maximal disturbance of this mode is between the North Atlantic and Europe rather than over the Caspian Sea or the northern side of the thermal source of the Indian monsoon. Therefore, although there is a close relationship between the zonally asymmetric mode and the “Silk Road” circulation pattern, their formation mechanisms are likely different.

PC2 has some interdecadal variation characteristics, and its correlation with Atlantic SST decreases after the trend is removed. Therefore, we calculate the correlation between PC2 and the Atlantic Multidecadal Oscillation (AMO) index by using NCEP data. As shown in Fig. 10, The PC2 sequence and the AMO index are very similar in their time variations. The correlation coefficient reaches 0.42, exceeding the 99% confidence level. Previous studies have shown the AMO could excite eastward-propagating Rossby wave trains across the Eurasian continent throughout the year. The anomalous upper-level divergence over North Atlantic associated with the AMO contributes to the Rossby wave source (Sun et al. 2015, 2016). Furthermore, the Asian jet stream in the upper troposphere plays an important role in the downstream propagation of perturbations from the North Atlantic region. It acts as a waveguide along which Rossby waves can propagate and tend to be trapped (Hoskins and Ambrizzi 1993; Watanabe 2004).

4.3 Possible physical processes

Figures 11 and 12 show the correlations of PC2, the summer soil moisture index, the preceding winter North Atlantic SST index with the surface temperature anomaly from preceding winter to simultaneous summer, respectively. The results indicate that on a seasonal timescale, the effects of the Atlantic SST and soil moisture are somewhat correlated. The

Fig. 10 Time series of PC2 and the AMO index

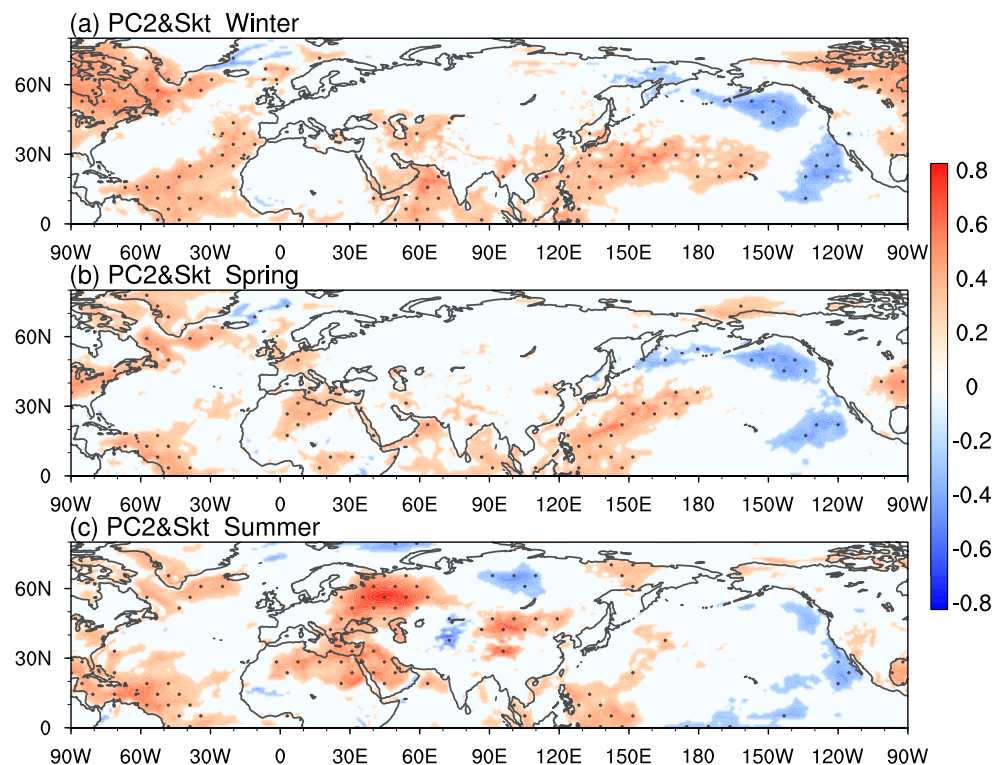


connection between the zonally asymmetric mode of the ASWJ and the surface thermodynamics (Fig. 11) is displayed as a transfer from the ocean to the continent occurring from winter to summer. In preceding winter, the jet reveals a relatively strong correlation with the upstream SST, and the correlation over the North Atlantic generally exhibits a tri-pole pattern from north to south. However, in summer, the jet is closely related to thermodynamic forcing of the land surface, and the impact of the SST gradually weakens. The regions with significant positive and negative correlations are distributed from west to east in the mid-high latitude regions of Eurasia. The SST pattern slightly weakens from winter to summer but is generally maintained, which stores the thermal forcing of Atlantic SST. The correlation pattern shown in

Fig. 12a–c is very similar to that shown in Fig. 11, i.e., the summer soil moisture is highly correlated with the preceding winter Atlantic SST while the simultaneous impact of the land surface is even stronger. The correlation between the soil moisture and thermodynamic moves from the ocean to the continent as the season evolves.

Meanwhile, there is obvious convergence of the T–N flux over regions between the North Atlantic and Europe, where Rossby waves gain energy. Because the subtropical jet jumps northward to near 40° N in summer, it can be considered that the jet plays the role of a “relay baton” in this process, and its waveguide effect “locks” the Rossby waves into the jet. Due to interactions between the waves and the jet, the heat that had been stored in the ocean at relatively high latitudes is

Fig. 11 Correlation between PC2 and surface temperature anomaly from preceding winter (a) and spring (b) to simultaneous summer (c). Dots indicate significant at the 95% confidence level



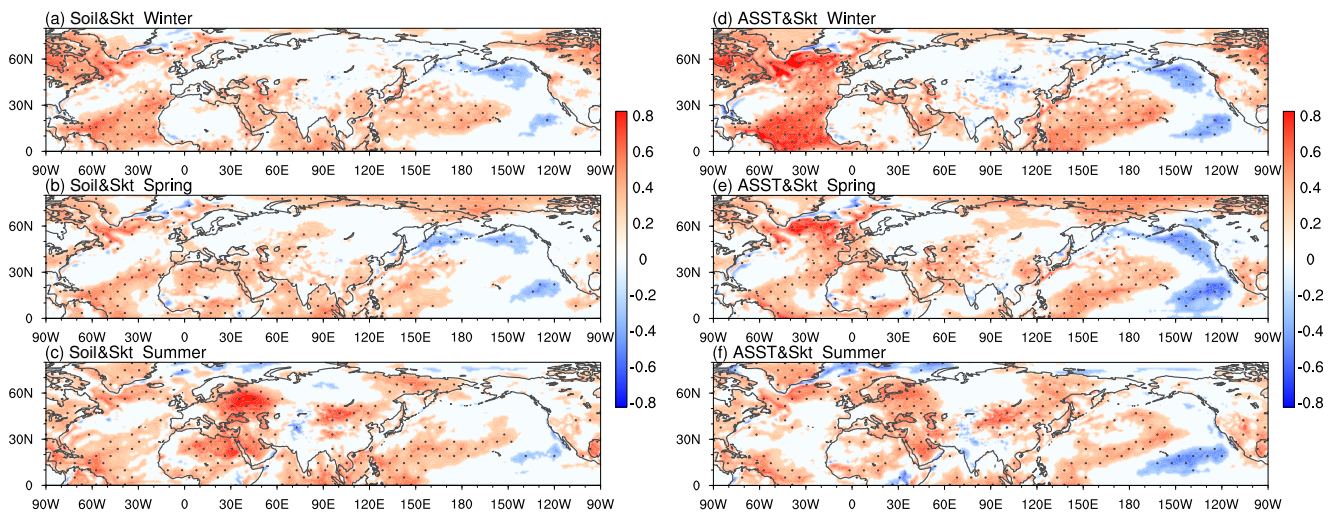


Fig. 12 As in Fig. 11, but PC2 is replaced by simultaneous summer upper layer soil moisture index (a–c) and preceding North Atlantic sea surface temperature index (d–f), respectively

transferred to the atmospheric waves and propagates downstream. In addition, summer soil moisture plays an important role in maintaining this process through the mechanism of evaporation positive feedback. We have regressed of soil moisture, sensible heat flux, surface temperature, and precipitation on PC2 (not shown). The areas with significant regression are relatively consistent, corresponding to the anomalous centers of the zonally asymmetric variation of the jet stream. The relationship between dry/wet soil moisture, positive/negative surface temperature, enhanced/decreased sensible heat flux, and decreased/increased precipitation means the surface thermal and precipitation anomalies in these regions have a positive feedback process corresponding to the atmospheric circulation anomalies. Such a process causes the underlying surface to interact with the upper circulation, affecting the zonally asymmetric variation of the jet stream. We can understand that, on the one hand, the abnormal soil moisture affects the abnormal heating of the atmosphere, causing changes in the circulation. On the other hand, the abnormal circulation also affects the precipitation and then causes the soil moisture abnormality.

Besides, the SST correlations with PC2 are significant not only in North Atlantic but also over the Northwest Pacific (Figs. 11 and 12). In fact, this SST correlation pattern corresponds to the Atlantic–Pacific trans-basin mode (Wang 2006; Keenlyside and Latif 2007). The warm SST anomaly generates anomalous ascent and upper-level divergence over North Atlantic. The associated upper-level outflows converge towards North Pacific, leading to compensating subsidence along with an anomalous high there, which weakens the Aleutian low and decreases the wind speed of westerlies. The wind changes induce a subtropical North Pacific SST warming through wind–evaporation–SST effect. In response, the surface winds converge towards the North Pacific SST warming center, leading to an anomalous cyclonic circulation

and low pressure over the Northwest Pacific region. The teleconnection further develops into a SST warming pattern due to the SST–sea level pressure–cloud–longwave radiation positive feedback (Sun et al. 2017).

This process reflects the coordination between the ocean, land, and atmosphere on a seasonal timescale. Results of some studies also support our point of view from a different perspective: Cui et al. (2015) and Wu et al. (2009, 2012a, 2016; Wu and Wu 2019) suggested that the tri-pole distribution of the SST in the North Atlantic can maintain from late winter to summer, and this SST warm core can trigger a steady stationary atmospheric Rossby wave train, which propagates eastward, altering the atmospheric circulation above Eurasia. Wang and He (2015) noted that atmospheric disturbances, such as the wave train of the “Silk Road” teleconnection pattern, are important factors that contribute to the natural disasters in the downstream region. In future predictions of the East Asian summer rainfall, the characteristics of the atmospheric circulation, and the forcing effects of SST should be comprehensively considered.

5 Conclusions

Based on the EOF decomposition of 200 hPa zonal wind anomaly during summer, we derived the three dominant spatial modes that characterize the ASWJ. The first and third modes describe the meridional displacement of the ASWJ and the variation in its overall strength, with a zonally symmetric pattern. Previous studies have achieved a relatively common understanding of these two modes. However, the second mode describes a zonally asymmetric distribution of the summer jet in East and West Asia and reflects the coordinated variations of its upstream and downstream systems. This

study focuses on analyzing the physical characteristics of the zonally asymmetric mode and its relevant mechanisms.

To understand the physical characteristics of the zonally asymmetric mode, we selected a temporal series of anomalous years in PC2 for composite analysis and derive the upper-level wind and pressure fields, the thermodynamics of the entire atmospheric layer, and the meridional temperature gradient at the middle and upper levels. The distribution of the upper-level composited wind field exhibits a zonally asymmetric horizontal structure that is inclined along southwest–northeast direction, and the four active centers of the anomaly are located north and south of the jet. The composited upper-level geopotential height anomaly exhibits a zonal wave train propagating along the jet at 40° N, and the anomalous positive and negative-value centers above East and West Asia correspond to the anomalous warm and cold centers in the troposphere, respectively. Under stable quasi-barotropic conditions, the wave signal propagates from west to east from the upstream mid-high latitude regions. In addition, the variation of the upper-level wind field is closely related to the atmospheric thermodynamic anomaly, and the anomalous distribution of the jet is significantly affected by the meridional temperature gradient of the troposphere, which complies with the thermal wind theorem.

On this basis, we also investigated the possible sources of the zonally asymmetric mode of the ASWJ by focusing on two aspects, i.e., the impact of external forcing and internal atmospheric processes. Results indicate that the thermal forcing of the underlying surface that is closely related to the zonally asymmetric mode mainly originates from the continent and the ocean at upstream mid-high latitude regions. The preceding North Atlantic SST, as a premonitory influence factor, can induce upper-level divergence anomalies, which lead to an anomalous Rossby wave source and excite an eastward-propagating wave train across the Eurasian continent. The summer soil moisture plays an important role in maintaining the thermodynamic anomaly through the mechanism of evaporation positive feedback. Moreover, the waveguide effect “locks” Rossby waves into the jet. Through the interaction between the waves and the jet, the heat that had been stored in the ocean at relatively high latitudes is transferred to the atmospheric circulation and propagates further downstream. The entire physical process reflects the coordination effect between the ocean, land, and atmosphere on a seasonal timescale.

Certainly, the study described in this paper only reveals a possible correlation between the zonally asymmetric mode of the jet’s anomalous variation and external forcing and internal atmospheric processes through observations, and the conclusion obtained can provide new perspectives for further understanding of the ASWJ variability. However, a more thorough and detailed analysis is needed to better understand the relevant mechanisms. In addition, numerical experiments mostly

treat the SST anomalies as the external forcing driving factors without considering the feedback from the land surface. The results described in this paper indicate that the summer soil moisture likely makes a significant contribution to the maintenance of the upper-level atmospheric circulation; therefore, previous analysis probably exaggerates the impact of the SST (since the impact of the land surface is set as default in the model). Of course, the specific contribution of the land surface to the ASWJ and the evolution of physical processes involved in the ocean–land–atmosphere coupling on a seasonal scale merits further validation through numerical experiments.

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