The Winter Concurrent Meridional Shift of the East Asian Jet Streams and the Associated Thermal Conditions

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ABSTRACT

In this study, the concurrent meridional shift of the East Asian polar-front jet (EAPJ) and the East Asian subtropical jet (EASJ) and the associated thermal conditions have been investigated. The concurrent meridional shift is dominantly characterized by an out-of-phase shift of the two jets, as an equatorward shift of the EAPJ and a poleward shift of the EASJ, and vice versa. This shift is linked with the dipole surface air temperature (SAT) anomaly over the Eurasian continent and a La Niña-like sea surface temperature (SST) anomaly. Associated with the dipole SAT anomaly, the meridional temperature gradient (MTG) anomaly exhibits a tripole pattern from low to high latitudes over the Eurasian continent, as well as an enhanced maximum eddy growth rate and an anomalous divergence of Eliassen–Palm flux (E–P flux) over the regions between the EAPJ and EASJ. Additionally, the synoptic-scale transient eddy activities (STEAs) significantly decrease over the high latitudes and enhance between the EAPJ and EASJ. All the anomalies would benefit the equatorward and poleward shift of the EAPJ and EASJ, respectively. The MTG, E–P flux and STEA anomalies are also indicated in that associated with the Niña-like SST anomaly. Particularly, the variations are evident in low latitudes. The pathway of the stationary Rossby wave activity flux anomalies shows an eastward Rossby wave packet propagation along the southern portion of the EAPJ is associated with the SAT anomaly and that along the northern portion of the EASJ is associated with the SST anomaly. The relative contributions of the two thermal conditions have emphasized the role of the dipole SAT anomaly, based on multilinear regression.

1. Introduction

In general, there are two branches of westerly jet streams in the upper troposphere over East Asia around the year, the East Asian polar-front jet (EAPJ) and the East Asian subtropical jet (EASJ). The EAPJ is located in the baroclinic zone, which is mainly formed by the eddy momentum flux convergence (Panetta 1993; Lee 1997).

The EASJ is an important component of the global subtropical jet, which is driven by the angular momentum transport along the poleward shift of the Hadley cell (Held and Hou 1980; Hou 1998). The two jets are strongest in the boreal winter, lying zonally along the northern and southern flanks of the Tibetan Plateau, respectively (Xiao and Zhang 2012; Luo and Zhang 2015; Huang et al. 2017).

At the interannual scale, previous studies have emphasized the shift of the East Asian jet streams rather than the intensity variation in boreal winter (Lin and Lu 2005). The shift can reflect the interactions among

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different circulation systems (Zhang et al. 2006; Schiemann et al. 2009) and therefore impact the local weather and climate as well as downstream regions (Jhun and Lee 2004; Li et al. 2004; Zhou and Yu 2005; Zhou and Zou 2010). On the one hand, the shift of the EAPJ can affect the variation of atmospheric circulation systems (e.g., the East Asia trough, Mongolian high pressure, and the blocking high) and therefore affect severe weather events, such as persistent low-temperature events and cold waves over East Asia (Zhang et al. 1997; D. Wang et al. 2009; Kuang et al. 2016). The seasonal evolution of the EAPJ is consistent with that of precipitation over eastern China (Zhang et al. 2008). On the other hand, the shift of the EASJ is highly associated with precipitation variations over China (Liao et al. 2004; Kuang and Zhang 2006; Dong et al. 2010; Ma et al. 2011; Shen et al. 2011; Xuan et al. 2011; Sun and Yang 2012; Lu et al. 2013). For example, the equatorward shift of the EASJ can affect the vertical momentum flux via the secondary circulation system and reinforce the water vapor flux transportation, and therefore enhance the precipitation over southern China (Zhang et al. 2009; Wang et al. 2011; Li and Zhang 2013).

Many factors can lead to the variations of the East Asian jet streams, such as the external forcing and internal atmospheric variability. There is some typical external forcing, such as the anomalous sea surface temperature (SST) over the western North Pacific (Yang et al. 2002; Lu et al. 2010), the anomalous snow cover over the Eurasian region (Yang et al. 2004; Chen and Sun 2003) and the heating and cooling over the Tibetan Plateau (Huang et al. 2015; Xue and Zhang 2017; Li et al. 2018). In general, changes of the thermal conditions may alter the meridional temperature gradients in the troposphere (Seidel et al. 2008; Si et al. 2009; Yim et al. 2016) that affect the EAPJ and EASJ (Huang et al. 2017) via the thermal wind relation (Zhang and Huang 2011). Huang et al. (2017, 2019) have shown that the combination of the negative phase of the interdecadal Pacific oscillation and the positive phase of the Atlantic multidecadal oscillation would enhance the meridional temperature gradient and westerlies over the region between the two jets, and therefore contribute to the equatorward shift of the EAPJ and the poleward shift of the EASJ. Besides the thermal conditions, the shift of the two jets is also influenced by the internal atmospheric variability [e.g., the synoptic-scale transient eddy activity (STEAs)], based on the eddy–zonal flow feedback (Feldstein and Lee 1996; Carillo et al. 2000; Lorenz and Hartmann 2001, 2003; Eichelberger and Hartmann 2007; Ren et al. 2008; Li and Wettstein 2012). For example, the shift of the EAPJ is consistent with

that of the STEA band over East Asia during the transition period from April to June (Ren et al. 2010). Xiang and Yang (2012) have shown that the transient eddy vorticity forcing could reinforce the meridional shift of the EASJ, favoring a positive feedback in the wave–flow interaction.

Recently, many studies have highlighted the concurrent variation of the two jets rather than the independent variation, since the concurrent variation can reflect the combined variation of the low- and high-latitude circulations and therefore result in severe weather and climate events (Liao and Zhang 2013), such as the dipole precipitation anomaly over eastern China (Li and Zhang 2014; Huang et al. 2014; Zhu et al. 2016), the decrease of the spring persistent rainfall after 1998 (Huang et al. 2015), variation of the East Asian winter monsoon (Luo and Zhang 2015), and the recent winter precipitation changes over eastern China (Huang et al. 2017). However, previous studies on the concurrent variation of the two jets mainly emphasized the intensity variation instead of the meridional shift variation. Some recent studies (Luo and Zhang 2015; Xue and Zhang 2017) have mentioned the variation of the meridional shift, but they do not separate the concurrent shift and the concurrent intensity variations. Moreover, the possible mechanism is still an open issue.

In all, we try to answer the following questions in this study: 1) What is the interannual variation of the concurrent meridional shift of the EAPJ and EASJ in the boreal winter? 2) What are the possible mechanisms for the concurrent meridional shift of the two jets?

The paper is organized as follows. The data and the methods are described in section 2. Section 3 presents the characteristics of the concurrent meridional shift of the EAPJ and EASJ. Possible mechanisms for the concurrent meridional shift of the two jets are proposed from the perspective of thermal conditions in section 4. Conclusions and discussion are provided in section 5.

2. Data and analysis methods

a. Data

The datasets used in this study include the following products covering 63 boreal winters (December–February) from 1951/52 to 2013/14:

- 1) The monthly and daily data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996), with a $2.5^\circ \times 2.5^\circ$ horizontal resolution and 17 levels in the vertical direction. The variables include the zonal wind, meridional wind,

surface pressure, air temperature, and geopotential height. For comparison, the ECMWF interim reanalysis (ERA-Interim) during 1979–2014 with a $\sim 0.75^\circ \times 0.75^\circ$ horizontal resolution and eight levels (consistent with the NCEP–NCAR reanalysis datasets) in vertical direction is also used (Dee et al. 2011).

- 2) The global monthly SST from the Hadley Center Sea Ice and Sea Surface Temperature dataset (HadISST) with a resolution of $1^\circ \times 1^\circ$ (Rayner 2003).
- 3) The global monthly surface air temperature (SAT) from the Climatic Research Unit (CRU; Harris et al. 2014) and from the University of Delaware (https://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html) with a resolution of $0.5^\circ \times 0.5^\circ$.

b. Methods

We followed four steps to obtain the concurrent meridional shift of the two jets:

- 1) The active regions of the two jets are defined following Ren et al. (2011): a jet core is identified if the wind speed at 300 hPa is higher than 30 m s^{-1} for any given day and grid point and the wind speed at the central point is larger than its eight surrounding points.
- 2) The location of the jet axis is represented by the latitude of the maximum westerly flow at each longitude, based on the winter-mean wind speed at 300 hPa (Zhang et al. 2006).
- 3) The 300-hPa jet axis anomaly is defined as the deviation from the position of the jet axis (Xiang and Yang 2012).
- 4) Following Xiang and Yang (2012), the 2.5–8-yr bandpass-filtered jet axis is used to emphasize the interannual variability. The empirical orthogonal function (EOF) analysis against the 2.5–8-yr bandpass-filtered jet axis anomaly along the longitude band 70° – 110°E (where the active region of the two jets is detected in the first step) is performed to reveal the dominant interannual variation of the concurrent meridional shift of the EAPJ and EASJ.

The meridional temperature gradient over a tropospheric layer is estimated as $\Delta T/a\Delta\phi$, where ΔT is the

difference of the vertically averaged temperature from the surface to 300 hPa between two adjacent zonal bands with a latitude distance of $\Delta\phi$ within 20° – 70°N and a is Earth's radius.

To understand the STEA variations associated with that of the jets, the maximum eddy growth rate (MEGR), the STEA kinetic energy K_e , and the Eliassen–Palm vector (E-P flux) are analyzed.

Hoskins and Valdes (1990) proposed that the mid-latitude STEA was largely ascribed to the atmospheric baroclinicity, which can be measured by the MEGR (Eady 1949) with the following formula:

$$\text{MEGR} = 0.31 \left(\frac{f}{N} \right) \left(\frac{dV}{dz} \right), \quad (1)$$

where f refers to the Coriolis parameter, N represents the Brunt–Väisälä frequency, V denotes the horizontal wind velocity, and z is the vertical height.

The intensity of K_e is calculated as

$$K_e = \frac{1}{2} \overline{(u'^2 + v'^2)}, \quad (2)$$

where u and v refer to the zonal and meridional wind speed, respectively, the overbar denotes the time mean in the boreal winter, and the primes represent 2.5–8-day perturbations by the bandpass filter (Murakami 1979).

The E-P flux is defined as

$$\mathbf{E} = (\overline{v'^2 - u'^2}, -\overline{u'v'}). \quad (3)$$

The signs in Eq. (3) have the same meaning as in Eq. (2). The divergence of $\mathbf{E}$ corresponds to the forcing on the horizontal circulation by enhancing the mean westerly flow, and vice versa (Hoskins et al. 1983).

To quantitatively estimate the horizontal propagation of stationary Rossby waves, the wave activity flux vector $\mathbf{W}$ is calculated in the expression formulated by Takaya and Nakamura (2001):

$$\mathbf{W} = \frac{p \cos \phi}{2|\mathbf{U}|} \left\{ \begin{aligned} & \frac{u}{a^2 \cos^2 \phi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \left(\frac{\partial^2 \psi'}{\partial \lambda^2} \right) \right] + \frac{v}{a^2 \cos \phi} \left(\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right) \\ & \frac{u}{a^2 \cos \phi} \left(\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right) + \frac{v}{a^2} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \left(\frac{\partial^2 \psi'}{\partial \lambda^2} \right) \right] \\ & \frac{f_0^2}{N^2} \left[\frac{u}{a \cos \phi} \left(\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial z} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial z} \right) + \frac{v}{a} \left(\frac{\partial \psi'}{\partial \phi} \frac{\partial \psi'}{\partial z} - \psi' \frac{\partial^2 \psi'}{\partial \phi \partial z} \right) \right] \end{aligned} \right\}, \quad (4)$$

FIG. 1. The climatological zonal wind (contours; m s^{-1}) and horizontal jet core (shaded) at 300 hPa in the boreal winter during 1951/52–2013/14. The red (blue) solid line indicates the climatological jet axis of the EAPJ (EASJ) at 300 hPa. The topography of the Tibetan Plateau is denoted by the thick black line.

where $\mathbf{U} = (u, v)$ is horizontal wind vector, $p = (\text{pressure}/1000 \text{ hPa})$ is the normalized pressure, and ψ' is the streamfunction anomaly. This flux is independent of wave phases and parallels the group velocity in a zonally varying basic flow.

Correlation and regression analyses are also applied in this study. To quantify the relative contribution of the two thermal conditions to the concurrent shift of the two

jets, multilinear regression is used. The statistical significance of the regression coefficient is assessed using a Student's t test at the 95% confidence level.

3. The concurrent meridional shift of the EAPJ and EASJ

The horizontal distribution of the climatological occurrence frequency of the jet core at 300 hPa in the boreal winter is shown in Fig. 1. The jet cores are located at the northern and southern flanks of the Tibetan Plateau, corresponding to the active regions of the EAPJ and EASJ, respectively (Pena-Ortiz et al. 2013; Luo and Zhang 2015; Huang et al. 2017). Particularly, the jet cores occur more frequently over the EASJ region than the EAPJ region. Following Liao and Zhang (2013) and Huang et al. (2017), 70° – 110°E is chosen as the active region of the EAPJ and EASJ in boreal winter to investigate the concurrent meridional shift of the two jets.

The EOF analysis is used to capture the dominant concurrent meridional shift of the two jets. The first leading EOF mode explains 66% of the total variance, revealing that the EAPJ and EASJ have experienced a prominent meridional shift (Fig. 2a). As shown in Fig. 2a, an obvious out-of-phase variation in the

FIG. 2. (a),(c) The first EOF mode of the EAPJ (blue) and EASJ (red) axis anomalies at 300 hPa in the boreal winter and (b),(d) the time series of the corresponding principal component of the first EOF mode from (left) NCEP–NCAR for 1951–2013 and (right) ERA-Interim for 1979–2013.

meridional shift of the EAPJ and EASJ is detected. This suggests a short distance between the EAPJ and EASJ (short-distance case) or a far distance between them (far-distance case). A repeat analysis of the ERA-Interim datasets for the period of 1979–2013 further confirms the result, which is shown in Figs. 2c and 2d. Although the time period is not consistent in the two reanalysis datasets, similar leading EOF patterns have been detected by both datasets. The differences between the two reanalysis datasets are largely due to differences of the model resolution (figure omitted).

To examine the concurrent meridional shift of the two jets, the regressions of zonal winds against the normalized PC1 are shown in Fig. 3. The latitudinal cross section of the westerly anomaly demonstrates a tripole pattern around the climatological EAPJ and EASJ axes at 300 hPa from 10° to 80°N. Two negative wind anomalies are located at ~20° and 65°N, and a positive zonal wind anomaly is located at ~45°N (Fig. 3a). The horizontal distribution of the regressed zonal wind anomalies at 300 hPa is shown in Fig. 3b, indicating a notable anomalous cyclone and an anomalous anticyclone around the EAPJ and EASJ axes, respectively. Correspondingly, the EAPJ and EASJ would shift equatorward and poleward, respectively. We also noticed that the concurrent shift of the two jets has mainly appeared over the Tibetan Plateau (Fig. 3b). This may imply the dominant role of the large-scale topography on the concurrent meridional shift of the two jets (Huang et al. 2015; Xue and Zhang 2017). In particular, the intensity of the wind anomaly around the EAPJ axis is substantially larger than that around the EASJ axis, corresponding to the far greater shift of the EAPJ than the EASJ (Fig. 2a). Thus, PC1 can reflect the concurrent meridional shift of the EAPJ and EASJ (the out-of-phase shift of the two jets) at the interannual time scale. The normalized PC1 is defined as the jet location index (JLI) in this study.

4. The possible mechanisms for the concurrent meridional shifts of the EAPJ and EASJ

In this section, we investigated the possible mechanisms of the interannual variation of the concurrent meridional shift of the two jets from the perspective of thermal conditions, including the variation of the SAT and SST. As mentioned in section 1, the thermal conditions would affect the meridional temperature gradient and STEA, and therefore impact the concurrent shift of the two jets. Thus, we first detected the significant thermal anomalies and then analyzed the associated meridional temperature gradient and STEA anomalies. Although there are two types of the concurrent variability

FIG. 3. (a) Latitudinal cross section of zonal wind anomalies (contours; m s^{-1} per unit index) averaged over 70°–110°E regressed against the JLI in the boreal winter. The red (purple) circle indicates the climatological position of the EAPJ (EASJ) axis at 300 hPa. The black shaded area shows the topography of the Tibetan Plateau. (b) The horizontal distribution of zonal wind anomalies (contours; m s^{-1} per unit index) and wind velocity anomalies (vectors; m s^{-1} per unit index) at 300 hPa regressed against the JLI in the boreal winter. Areas of statistical significance exceeding the 95% confidence level are shaded. The red (purple) solid line indicates the climatological horizontal jet axis of the EAPJ (EASJ) at 300 hPa. The topography of the Tibetan Plateau is denoted by the thick green line.

(short-distance case and far-distance case), they largely mirror each other. Thus, we only analyzed the circulations associated with the positive PC1, which favors the equatorward shift of the EAPJ and the poleward shift of the EASJ (short-distance case).

a. The associated SAT variations

The regression of SAT against the JLI is shown in Fig. 4. Because of the uncertainties of the SAT over the Tibetan Plateau (Zhu et al. 2017), we chose two datasets to analyze. They show consistent results: two significant SAT anomalies with an out-of-phase variation are located over the Tibetan Plateau and mid- to high-latitude areas, with a warm anomaly over the Tibetan Plateau

FIG. 4. Regressions of the surface air temperature against the JLI in the boreal winter (contours; $^{\circ}\text{C}$ per unit index) from (a) CRU and (b) the University of Delaware. Areas of statistical significance exceeding the 95% confidence level are shaded. The dashed red and blue boxes indicate the key regions for calculating the surface air temperature index (SATI). The topography of the Tibetan Plateau is denoted by the thick green line.

and a cool anomaly over mid- to high latitudes. We selected the SAT over two significant regions (red and blue boxes in Fig. 4) to define this out-of-phase SAT variation as the normalized SAT variation index (SATI), with the following formula:

$$\text{SATI} = \text{SAT}[27.5^{\circ}\text{--}35^{\circ}\text{N}, 75^{\circ}\text{--}103^{\circ}\text{E}] - \text{SAT}[55^{\circ}\text{--}65^{\circ}\text{N}, 70^{\circ}\text{--}110^{\circ}\text{E}]. \quad (5)$$

The square brackets denote the regionally averaged SAT. A large SATI indicates a relatively cooler condition over the EAPJ region than the EASJ region. The regressed wind anomalies against the SATI have been shown in Fig. 5. A significant negative–positive–negative wind anomaly is located from the low to high latitudes, which resembles the zonal wind anomaly associated with the JLI (Fig. 3). This suggests that the SATI can explain the dominant interannual variation of the meridional shift of two jets.

Regression of the meridional temperature gradient against the SATI is shown in Fig. 6. A significant tripole meridional temperature gradient anomaly pattern exists from 20° to 80°N . The positive anomalies are over the northern side of the EAPJ and southern side of the EASJ, while the negative anomaly lies between the regions of the EAPJ and EASJ axis. In particular, the meridional temperature gradient anomalies are more significant over the high latitudes than that over the low latitudes. Since the climatological meridional temperature gradient is negative over the Northern Hemisphere due to the decreasing temperature from south to north, the negative (positive) meridional temperature gradient anomaly would strengthen (weaken) winds there, based on the thermal wind relation (Zhang et al. 2006). The anomalous meridional temperature gradient would lead to a westerly acceleration over the region between the EAPJ and EASJ axis, indicating the

equatorward shift of the EAPJ and a poleward shift of the EASJ.

Figure 7 shows the regressed MEGR (green contours), the K_e (shading), and the E-P flux divergence (black contours) anomalies against the SATI. The positive MEGR anomaly is located between the axis of the EAPJ and EASJ in the lower troposphere

FIG. 5. As in Fig. 3, but for the latitudinal cross section of the zonal wind anomalies (contours; m s^{-1} per unit index) averaged over $70^{\circ}\text{--}110^{\circ}\text{E}$ regressed against the SATI in the boreal winter.

FIG. 6. Regressions of the meridional temperature gradient (MTG) (contours; $10^{-6} \text{ }^{\circ}\text{C m}^{-1}$ per unit index) integrated from the surface to 300 hPa against the SATI in the boreal winter. Areas of statistical significance exceeding the 95% confidence level are shaded. The red (purple) line indicates the climatological horizontal jet axis of the EAPJ (EASJ) at 300 hPa. The topography of the Tibetan Plateau is denoted by the thick green line.

(850–1000 hPa), where the sensitive region of the MEGR is located (Lunkeit et al. 1998). This positive MEGR anomaly would benefit the westerly flow between the two jets, possibly associated with the increased horizontal temperature gradients (Lehmann et al. 2014). Meanwhile, the large negative K_e anomaly is mainly located at the northern side of the EAPJ axis at ~ 250 hPa, while the small positive K_e anomaly is at the northern side of the EASJ axis at 200 hPa. These would benefit the equatorward shift of the EAPJ and the poleward shift of the EASJ. In fact, K_e anomalies over the EASJ region are not as significant as those over the EAPJ region. Since the EAPJ is mainly formed by the eddy momentum flux convergence (Panetta 1993), the equatorward shift of EAPJ is more consistent with the variation of STEA at the interannual time scale than that of poleward shift of the EASJ (Li and Wettstein 2012). Based on the theory of wave–flow interaction, variation of the time-mean flow induced by the STEA can be identified by the divergence of the E–P flux (Gong et al. 2011). Generally, the divergence region is related to the acceleration of mean westerly flow and the convergence responds to the westerly deceleration (James 1994, 78–79; Hoskins et al. 1983). As shown in Fig. 7, there are two significant meridional dipole patterns of the divergence anomalies of E–P flux (black contour) along the EAPJ axis and the EASJ axis. Associated with the SATI, a significant divergence (convergence) anomaly is located at the southern (northern) side of the EAPJ axis, indicating the energy conversion from the STEA to the mean westerly flow (from the mean westerly flow to the STEA), where the

FIG. 7. Latitudinal cross section of the regressed maximum eddy growth rate (MEGR) anomalies (green contours; 10^{-1} day^{-1} per unit index), the K_e anomalies (shaded; $\text{m}^2 \text{ s}^{-2}$ per unit index), and the divergence anomalies of E–P flux (black contours; 10^{-6} m s^{-2} per unit index), averaged over 70° – 110°E against the SATI in the boreal winter. The red (purple) circle indicates the climatological position of the EAPJ (EASJ) axis. The black shaded area indicates the topography of the Tibetan Plateau.

westerly flow strengthens (weakens) (Huang et al. 2014). Similarly, a significant divergence (convergence) anomaly is located at the northern (southern) side of the EASJ axis, and therefore results in the poleward shift of the EASJ. Note that we should not ignore the weak convergence anomaly along 40° – 50°N , which may reduce the westerly flow. However, the enhanced MEGR over the region, combined with the two strong divergence anomalies of E–P flux along 30° and 50°N , may enhance the westerly flow there.

b. The associated SST variations

To find significant SST anomalies associated with the concurrent meridional shift of the two jets, the regression of SST against the JLI is shown in Fig. 8. A significant negative SST anomaly is located over the tropical central–eastern Pacific, which resembles the La Niña-like SST anomaly. To investigate the impact of the SST anomaly on the maintenance of the thermal and transient eddy effects associated with the concurrent meridional shift of the EAPJ and EASJ, a normalized SST variation index (SSTI) is defined as follows:

FIG. 8. Regressions of the SST (contours; °C per unit index) against the JLI in boreal winter. Areas of statistical significance exceeding the 95% confidence level are shaded. The dashed red box indicates the key region for calculating the sea surface temperature index (SSTI).

$$\text{SSTI} = -\text{SST}[5^{\circ}\text{S} - 5^{\circ}\text{N}, 80^{\circ} - 145^{\circ}\text{W}]. \quad (6)$$

The square brackets denote the regional averaged SST. Similarly, to further examine the associated wind anomalies, the zonal wind anomalies regressed against the SSTI are shown in Fig. 9. Although the anomaly in the high latitudes is weak, the wind anomalies are consistent with those are shown in Fig. 3, indicating the equatorward shift of the EAPJ and the poleward shift of the EASJ.

FIG. 9. As in Fig. 3, but for the regressions against the SSTI in boreal winter.

FIG. 10. As in Fig. 6, but for the regressions against the SSTI in boreal winter.

Figure 10 shows the regression of the meridional temperature gradient anomaly against the SSTI. A significant meridional dipole anomaly is along the EASJ axis, with a negative meridional temperature gradient anomaly over the northern part of the EASJ. This would enhance the westerly flow there via the thermal wind relation. A small positive meridional temperature gradient anomaly can also be observed along the northern side of the EAPJ axis, which would reduce the westerly flow there. It suggests that the La Niña-like SST anomaly may be more closely related to the meridional shift of the EASJ than of the EAPJ. Figure 11 shows the regressed MEGR (green contour), the K_e (shading) and the E-P flux divergence (black contour) anomalies against the SSTI. Negative MEGR and K_e anomalies are along the southern side of the EASJ, and therefore

FIG. 11. As in Fig. 7, but for the regressions against the SSTI in boreal winter.

FIG. 12. Regressions of geopotential height (shaded; gpm per unit index) and wave activity flux (vectors; $\text{m}^2 \text{s}^{-2}$ per unit index) at 300 hPa against the (a) SATI and (b) SSTI in boreal winter.

could reduce the westerly flow there. Two divergence anomalies of E-P flux are also found along the northern part of the EASJ axis and along the EAPJ axis, suggesting that the EAPJ would be enhanced and the EASJ would shift poleward.

We should notice that some previous studies have indicated the possible linkage between the SST variation over the eastern equator Pacific and the jet variations. For example, Huang et al. (2014) found that the La Niña-like SST anomaly would intensify the Walker circulation in the boreal summer, which could influence cyclone anomaly over the western Pacific (Wang et al. 2000). Correspondingly, the convective activities triggered over the western Pacific would benefit the meridional teleconnection and therefore affect the EASJ (Lu 2004). Sakai and Kawamura (2009) have revealed that the ENSO-related tropical convective forcing would affect the East Asian jet streams in the boreal winter, via the stationary Rossby wave propagation along the South Asian waveguide. Wang et al. (2000) and Zhang et al. (1996) also proposed the mechanisms that describe how the tropical SST anomalies affect the East Asian circulations, via the Pacific–East Asian teleconnection. As shown in Figs. 5b and 5c in Wang et al. (2000), a giant cyclonic anomaly is located over Southeast Asia for El Niño composites. Consequently, the anomalous easterly wind along 30° – 40°N would weaken the westerly flow there (Luo and Zhang 2015). Since El Niño and La Niña composites largely mirror each other (Wang et al. 2000), atmospheric circulation anomalies show an anticyclonic pattern over Southeast Asia associated with La Niña events (Wang et al. 2000). Associated with the anticyclonic anomaly, the EAPJ

and EASJ would exhibit an equatorward shift and a poleward shift, respectively, which is consistent with the regressed wind anomalies (Fig. 9).

c. The Rossby wave propagations associated with the SAT and SST variations

Sections 4a and 4b show the possible linkages between the SAT and the SST variation and the meridional variation of the EAPJ and the EASJ, via the modulation of the meridional temperature gradient, MEGR, K_e , and E-P flux. Since the external forcing (SAT and SST variation) may generate the planetary wave modulations, we further investigated the possible propagation by analyzing the stationary Rossby wave activity fluxes and the geopotential anomaly fields in the entire extratropical Northern Hemisphere regressed against the SATI and SSTI (Fig. 12).

Associated with the SATI (Fig. 12a), wave activity flux anomalies extend eastward from the Barents Sea (70°N , 40°E) to East Asia along 50° – 55°N , that is, the southern portion of the EAPJ. This high-to-midlatitude wave train is characterized by positive geopotential height anomalies over the Barents Sea and a negative anomaly over northern Asia. Modulated by the Arctic Oscillation, the Arctic sea ice could influence the jet variabilities by varying the thermal conditions (Honda et al. 2009; Mori et al. 2014). Associated with the SSTI (Fig. 12b), wave activity flux anomalies extend eastward from North Africa (40°N , 20°E) to East Asia along the 40°N , that is, the northern portion of the EASJ. However, the SSTI-related wave train is weaker than the SATI-related one, as the largest wave activity fluxes anomalies are located over the North Pacific.

FIG. 13. Regressions of (a) geopotential height (shaded; gpm per unit index) at 500 hPa and (b) sea level pressure (shaded; hPa per unit index) against the SATI in boreal winter. The black lines are the climatological-mean geopotential height at 500 hPa in (a) and the sea level pressure in (b).

The geopotential height anomalies are quite consistent, indicating the negative height anomalies (anomalous cyclone) over northern Asia and the positive height anomalies (anomalous anticyclone) over the southern Tibetan Plateau and high latitudes. Associated with the cyclonic and anticyclonic anomalies, the EAPJ and EASJ would exhibit an equatorward and a poleward shift, respectively. These wind anomalies are consistent with the regressed wind anomalies against the SATI (Fig. 5) and SSTI (Fig. 9).

d. The relative contribution of the SAT and SST variations

To confirm the results, we have repeated all the analyses above using the ERA-Interim datasets (figures omitted), and the results are similar. Thus, we conclude that both the SATI and SSTI would affect the out-of-phase shift of the two jets. To quantify the contribution of the SATI and SSTI to the concurrent meridional shift of the two jets, we performed a multilinear regression. This method is acceptable because the correlation of the two time series of the SATI and SSTI is weak, with a correlation coefficient of 0.0757. The multilinear regression equation is $JLI \approx 0.493 \times SATI + 0.168 \times SSTI$. The skill for this regression reaches 0.74. Since the regression coefficient of the SATI is higher than that of the SSTI, the multilinear regression indicates that the dipole SAT anomaly is more important than the negative SST anomaly over the central-eastern Pacific with regard to the impact on the concurrent meridional shift of the two jets.

Previous studies have mentioned the changes of the EAPJ and EASJ in general circulations associated with the East Asian winter monsoon, such as the geopotential height fields (L. Wang et al. 2009; Huang et al. 2012; Liu et al. 2014; Oh et al. 2017). For example, L. Wang et al. (2009) indicated that the variation of the East Asian trough axis is closely associated with the midlatitude baroclinic process and therefore represents the intensity of the EAPJ. Luo and Zhang (2015) mentioned that a southward shift of the EAPJ occurs with northwestward displacement of the Siberian high and an enhanced northern East Asian trough. To give a full picture of present results, we further examined the geopotential height at 500 hPa and the sea level pressure associated with the SATI (Fig. 13). The regressed 500-hPa geopotential height anomaly (Fig. 13a) increases over the low-to-midlatitude region around 10°–30°E and over the Arctic region but decreases over the Eurasian continent. The horizontal structure of the geopotential height anomaly shows a clear wave train pattern at 500 hPa. The wave train may be interpreted as quasi-stationary Rossby waves trapped on the East Asian jet waveguide, particularly for the EASJ (Branstator 2002; Watanabe 2004; Takaya and Nakamura 2013). Combined with the wave activity flux variations observed from the Barents Sea to Siberia (Fig. 12), some upstream factors may lead to the change of surface air temperature and temperature gradient over Siberia, and therefore affect the variation of the two jet streams, via the hemispheric-scale circulation anomaly (Fig. 13). Similarly, the regressed sea level

pressure anomalies resemble a negative phase of the Arctic Oscillation (Xue and Zhang 2017). The correlation coefficient between the SATI and the Arctic Oscillation index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml) is -0.24 , which is significant at the 90% confidence level. Watanabe (2004) also revealed that on the interannual time scale, the North Atlantic Oscillation (NAO) signal is collocated with a wave train along the EASJ. These results have established a possible linkage among the SATI, the Arctic Oscillation, and the meridional shift of the two jets in the boreal winter, but further investigation is needed.

5. Conclusions and discussion

In this study, the interannual variability of the concurrent meridional shift of the EAPJ and the EASJ in the boreal winter is investigated. This shift is revealed by the leading EOF of the filtered 300-hPa EAPJ and EASJ axis anomalies. At the interannual time scale, the two jets exhibit a prominent meridional shift between 70° and 110°E , indicating an obvious out-of-phase variation of the two jets. This variation suggests that as the EAPJ shifts poleward, the EASJ shifts equatorward, and vice versa.

Two significant thermal conditions, the dipole SAT anomaly over the Eurasian continent and the La Niña-like SST anomaly, have contributed to the out-of-phase shift of the two jets. Associated with the dipole SAT anomaly, the tripole meridional temperature gradient pattern is located from the low to high latitudes over the Eurasian continent, and the enhanced MEGR anomaly is located over the regions between the EAPJ and the EASJ. Meanwhile, the anomalous divergence of the E-P flux appears along the region from 40° to 50°N , which would result in the equatorward shift of the EAPJ and the poleward shift of the EASJ. Associated with the La Niña-like SST anomaly, the meridional temperature gradient and the STEA anomalies are quite similar to those related to the dipole SAT anomaly. However, the anomalies are more significant in the low latitudes than the high latitudes. This indicates that the SSTI mainly contributes to the meridional shift of the EASJ rather than that of the EAPJ. The pathway of the stationary Rossby wave activity flux anomalies also shows that an eastward Rossby wave packet propagation along the southern portion of the EAPJ associated with the SAT anomaly and along the northern portion of the EASJ associated with the SST anomaly. Correspondingly, the negative height anomalies (anomalous cyclones) over northern Asia and the positive height anomalies (anomalous anticyclones)

over the southern Tibetan Plateau and high latitudes would result in the equatorward shift of the EAPJ and the poleward shift of the EASJ.

The relative contributions of the two thermal conditions have been further analyzed by multilinear regression, which emphasizes the role of the dipole SAT anomaly. It should be noted that the dipole SAT variation may be closely related to the thermal conditions over the Tibetan Plateau, which has been mentioned as an important factor for the variations of the two jets, via the associated cyclone–anticyclone anomaly around the Tibetan Plateau (Huang et al. 2015). Given the importance of the dipole SAT variation, the role of the thermal condition of the Tibetan Plateau needs further investigation by numerical experiments.

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