ABSTRACT

This study investigates the linkage between East Asian winter monsoon variability and upper-level jets, with particular focus on the East Asian polar front jet (PJ) and its concurrent variation with the subtropical jet located to the south of the Tibetan Plateau (TSJ). The winter upper-level zonal wind variations over the Asian landmass (70°E–120°E) are dominated by two principal modes (i.e., meridional displacement of the PJ and out-of-phase variation in the intensity of the TSJ and PJ) and they are closely linked to the EAWM northern mode and southern mode, respectively. Southward shifting of the PJ concurs with northwestward displacement of the Siberian high (SH), an enhanced northern East Asian trough, leading to cold winter in northern East Asia. Meanwhile the simultaneous TSJ intensification and PJ weakening is linked to an amplified SH, a southward shift of the Aleutian low (AL), a strengthened southern East Asian trough, and a wavelike anomaly pattern extending from western Barents Sea downstream to East Asia at the 500-hPa level. Equatorward shift of the PJ is associated with La Niña conditions in the tropics and sea ice anomalies over the Arctic. An intensified TSJ and weakened PJ are preceded by autumn warming over the central and eastern Pacific Ocean and are linked to circulation anomalies induced by the extensions of stationary Rossby waves, as well as synoptic-scale transient eddy activity anomalies. Therefore, a combination of external forcing and internal atmospheric dynamics plays a role in driving the variations of two leading EOFs, and there is potential for seasonal forecasting of both modes.

1. Introduction

In East Asia, the climate variability in boreal winter is dominated by the East Asian winter monsoon (EAWM) system. The EAWM is one of the most energetic monsoon circulation systems affecting temperature and precipitation variations over East Asia in winter season. In January of 2008, central and southern China experienced an extreme cold snowstorm event with extensive economic damage, which broke the 57-yr record of low temperature. More recently in January 2010, low temperature and snowfall in northern China and Korea Peninsula also broke their 50- and 70-yr records, respectively. An active EAWM is accompanied by low temperature and strong gales of a cold wave (Chang et al. 2006) and can induce heavy rainfall over southern China. Therefore the EAWM has large social and economic impacts on East Asian countries, and the variability and accurate prediction of the EAWM have always been important issues.

The structure of the EAWM encompasses a large meridional domain and features distinct major components at different levels from lower troposphere to the tropopause. At the surface, the EAWM is characterized by the Siberian high (SH), Aleutian low (AL) (see Fig. 4b), and low-level northeasterlies along the East Asian coast. In the midtroposphere, the 500-hPa East Asian trough is located near Japan, marked by a meridionally tilted region of strong geopotential height gradient (see Fig. 4a; Wang et al. 2009). In the upper troposphere, the strong westerly jet stream dominates the circulation system over East Asia, which is referred to as the East Asian jet stream (EAJS) (Fig. 1). These three-dimensional components are inherently linked to each other (Jhun and Lee 2004). A strong EAJS manifests itself as northerly wind anomalies along the margin of East Asian continent, lower surface air temperature, and an intensified AL and SH at the surface; it also features an enhanced East Asian trough as well as a
strong subtropical jet stream (Chang et al. 2006; Jhun and Lee 2004). Many previous efforts have been devoted to exploring the EAWM variability and its mechanisms in terms of these components. Among them, many studies have stressed that the EAJS has significant influence on EAWM variability (Yang et al. 2002; Gong and Wang 2002; Jhun and Lee 2004). The EAJS significantly affects weather and climate anomalies locally in middle-to-high latitudes as well as over downstream regions. For example, comprehensive reviews about weather and climate effects of the EAJS are presented by Gong et al. (2001) and Yang et al. (2002). Therefore, understanding the variation of upper-level jets over East Asia and its association with EAWM variability as well as the variability of other EAWM components is important for accurate EAWM forecasting.

In boreal winter, observational evidence shows that the upper-level wind over East Asia is characterized by two jets in the upper troposphere and the lower stratosphere: the East Asian subtropical jet (SJ) and the East Asian polar front jet (PJ). Over the East Asian landmass, the PJ and SJ are separated from each other and are located along the southern side and poleward side of the Tibetan Plateau, respectively (Fig. 1). The division of the two jets is essentially rooted in the different dynamical processes involved in their formation (Held 1975; Rhines 1975; Held and Hou 1980; Lee and Kim 2003). Scientists have realized the importance of distinguishing SJs and PJs, and thus investigate their independent variability as well as their effects on East Asian climate. Many studies have illustrated the relationship between SJ variability and the EAWM. The subtropical westerly jet could reflect the EAWM intensity; that is, a strong SJ is associated with an intensified EAWM, and vice versa (Yang et al. 2002; Jhun and Lee 2004; Kuang and Zhang 2008; Ha et al. 2012; Liu et al. 2012; Chen et al. 2014a). On the other hand, the SJ is also closely related to temporal and spatial features of the EAWM (Yang et al. 2002; Kuang and Zhang 2008). Kuang and Zhang (2008) pointed out that the SJ shows in-phase relationships with the EAWM subsystems, and can reflect the variability of SH, AL, and East Asian trough intensity. In addition, the seasonal evolution of the PJ is also linked with the seasonal shift of the atmospheric circulation in East Asia, and thus correlated with winter rainfall in East China (Zhang et al. 2008). Jhun and Lee (2004) proposed an EAWM index that highlighted 300-hPa zonal wind shear. The wind shear index illustrates the connection between EAWM subsystems better than considering SJ and PJ influence separately. Therefore, we propose that joint variation of the SJ and PJ are closely connected with EAWM variability via their modulation of high- and low-latitude winter circulation. This motivates us to investigate the impact of joint variability of the two jets below.

Recently, studies have revealed that the concurrent variation of PJ and SJ serve as important indications of interaction between low- and high-latitude circulation.
systems and changes in general circulation over East Asia. Zhang and Xiao (2013) found that the out-of-phase variation mode in the intensity of SJ and PJ is intimately related to the atmospheric general circulation in mid-latitude East Asian region and significantly correlated with the EAWM index proposed by Jhun and Lee (2004). Furthermore, concurrent variation between the SJ and PJ is proven to act as an important signal associated with the cold and warm air activities in both climatological boreal winter and extreme events, as well as during the mei-yu season in summer (Liao and Zhang 2013; Zhang and Xiao 2013; Li and Zhang 2014; Ye and Zhang 2014; Huang et al. 2014). Hence, taking into account the variation of the two jets to investigate EAWM variability would enhance the interpretation of the interaction processes between circulation systems at different latitudes.

Many previous studies tend to measure EAWM strength with a single index. A review of existing literature indicates about the EAWM classifies four categories of EAWM indices (Wang and Chen 2010), including low-level wind indices (Ji et al. 1997; Chen et al. 2000; Hu et al. 2000; Yang et al. 2002), upper-level zonal wind shear indices (Jhun and Lee 2004), zonal–meridional pressure contrast indices (Guo 1994; Shi 1996; Wu and Wang 2002; Wang and Chen 2014), and East Asian trough indices (Sun and Li 1997; Cui and Sun 1999). However, recent studies about the EAWM have noted the extremely large meridional extent of the EAWM (0°–60°N) and argued that the climate anomalies associated with the EAWM may not be consistent between the middle-to-high and low latitudes in East Asia (Kang et al. 2009; Wang et al. 2010; Liu et al. 2012; Chen et al. 2014a). The notion that winter monsoon variability over East Asian region is dominated by two modes, the southern mode and northern mode, has been studied from the perspectives of surface temperature (Wang et al. 2010) and surface wind (Liu et al. 2012; Chen et al. 2014a). However, threedimensional structures of the two modes of the EAWM, especially the associated upper-level jet variability, have not been elaborated. Moreover, the viewpoint of stressing meridional differences in the EAWM system also indicates the necessity of considering both independent and concurrent variation of the PJ and SJ to understand the monolithic structure of the atmospheric circulation system related to the EAWM.

Therefore, in the context of distinct different EAWM variability between middle-to-high- and low-latitude East Asian areas, this study is motivated to unravel the impact of upper-level jet variability on the EAWM, with a focus on illustrating the influence of the PJ and its concurrent variation with the SJ. Based on the linkage between two jets and the EAWM, we will further elaborate the three-dimensional structure of the EAWM system, and discuss the possible reasons for the linkage. The rest of the paper is organized as follows. The dataset and analysis methods used in this study are described in section 2. Climatological distributions of the two jets and their dominant variation modes are presented in section 3. In section 4, EAWM variability associated with jet variation modes is discussed, followed by an analysis of the associated circulation features in section 5. We also explore the external forcings and the atmospheric wave activity embedded in jet variability modes to provide possible reasons for this linkage in section 6. A summary and discussion of the results are provided in section 7.

2. Data and methods

This study uses daily and monthly mean wind, geopotential height, sea level pressure (SLP), and surface temperature data from the National Centers for Environmental Prediction (NCEP)–National Center for the Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996), with a longitude–latitude resolution of 2.5° × 2.5°. The sea surface temperature (SST) data gridded at 2° × 2° resolution are derived from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST, version 3b) (Smith et al. 2008). The sea ice concentration (SIC) data are obtained from the Met Office Hadley Centre with a resolution of 1° × 1° available since 1870 (Rayner et al. 2003).

The time period analyzed in this study is 36 winters from 1979/80 to 2014/15. Wintertime means are constructed from the monthly means by averaging the data of December–February (DJF). Here the winter of 1979 refers to the 1979/80 winter.

The present study employs the mass-weighted empirical orthogonal functions (EOFs) analysis (Thompson and Wallace 2000) to extract the dominant patterns of upper-level jet variability. Correlation and regression analyses are applied to investigate the relationship between principal component (PC) time series and the spatial patterns. Composite analysis is performed based on time series of the principal variation modes of the jets. The synoptic eddy component of zonal and meridional winds within a period of 2.5–8 days was obtained by bandpass filtered technique following Murakami (1979).

3. Climatological distributions of the two jets and principal modes of variability

The winter mean zonal wind at the 300-hPa level, as shown in Fig. 1, exhibits strong westerly winds over East Asia. To unravel the distribution of the two jets, we calculate the wintertime occurrence numbers of the jet
stream at 300 hPa. A jet core is identified and the corresponding latitude and longitude are recorded if 1) the wind speed is equal to or greater than 30 m s\(^{-1}\) and 2) the wind speed is the local maximum of the surrounding eight grid points (Ren et al. 2010). As shown in Fig. 1, a jet core minimum occurs over the Tibetan Plateau, such that the two jets are clearly distinguishable from one another. The distribution of jet core numbers implies that the eddy-driven jet and the subtropical jet not only coexist, but also show discernable spatial distribution patterns over the East Asian landmass. For the region to the east of 120°E over the ocean, however, the distinction between the two jets disappears and is replaced by only one strong jet core belt, resulting in the strongest jet stream over the northwestern Pacific and Japan. Over the East Asian landmass, the PJ and SJ are separated from each other and are located along the southern side and poleward side of the Tibetan Plateau, respectively (Fig. 1). To the east of 120°E, the intensity of the SJ is greatly enhanced by the confluence of the PJ. In this study, the SJ is classified as the Tibetan Plateau branch (TSJ) or ocean branch (OSJ) according to the zonal position.

Climatological distributions of the jets suggest zonal asymmetries of jets over East Asia. To the west of 120°E over the land region, the two jets are clearly separated. Specifically, our analysis focuses on the jet variability over East Asia land area extending from 70° to 120°E. Figure 2 shows first two principal EOF modes of winter zonal-mean zonal wind averaged from 70° to 120°E. The EOF analysis is performed over the region of 20°–70°N at 1000–100 hPa. A dipole pattern centered at the eddy-driven jet dominates the leading EOF, which explains 42.5% of the total variance. Therefore, EOF1 depicts north–south shifting in the position of PJ. Meanwhile there is also a dipole mode center around the TSJ axis, which represents slight meridional displacement of TSJ since the two centers of the dipole are close to each other. In contrast with PJ, TSJ is steadier and stronger in intensity (Fig. 1) and therefore exhibits much less significant meridional migration. Over the land area, the meridional shift of PJ dominates the pattern of the first EOF mode. The second principal mode (accounting for 20.3% of the total variance) exhibits a dipole structure with the two anomaly centers located along the TSJ and PJ, respectively. Thus EOF2 is associated with a strengthening and weakening of upper-level jet at 300 hPa and depicts the out-of-phase relationship in the intensity between TSJ and PJ. It is notable that since the TSJ is climatologically much stronger than the PJ, EOF2 implies a larger relative change in the strength of the PJ than the TSJ. A regional perspective of the two jets over the East Asian landmass provides detail of the concurrent variation of the PJ and TSJ, which could be reflected by the two leading EOF modes.

Both PC1 and PC2 show notable interdecadal variability. An interdecadal change from a positive to a negative phase occurs around 1985 for both PC1 and
PC2. Since then PC2 has mainly exhibited a negative phase with some interannual variations, whereas PC1 has been in a negative phase before another transition to a positive phase in the early 2000s.

4. Relationship between leading variability modes of the jets and EAWM

As indicated by previous studies, the first two leading modes can represent the integral variation of atmospheric circulation in the midlatitude region. In this section we aim to clarify the possible links between the two variation modes of jets and EAWM variability.

To get an intuitive impression of the relationship between the two jets’ variation modes and the EAWM, we calculate correlation coefficients of PC1/PC2 time series with some EAWM indices (Table 1). Different categories of the EAWM indices are used to quantify the intensity of the EAWM, which can reflect typical EAWM components at different levels. Specifically, the indices include SLP indices, such as SH measured by the SLP over 40°–60°N, 80°–120°E; the zonal/meridional SLP gradient indices defined by Shi (1996) and Wang and Chen (2014); meridional wind at 850 hPa averaged over 20°–40°N, 100°–140°E (Yang et al. 2002); the East Asian trough index measured by area-averaged 500-hPa geopotential height over 30°–45°N, 125°–145°E (Sun and Li 1997); meridional shear of 300-hPa zonal wind (Jhun and Lee 2004) and 200-hPa zonal wind (Li and Yang 2010); and the integrated EAWM index associated with both the Mongolia–Siberian high and the Asia-wide meridional dipole anomaly of 500-hPa geopotential height (Hu et al. 2015). It is found that both PC1 and PC2 have significant correlation with most of the EAWM indices, except for the 850-hPa meridional wind–related index. PC2 is significantly correlated with the most common EAWM components (at the 99.9% confidence level), indicating that the out-of-phase relationship between the TSJ and PJ intensities is strongly linked to EAWM variability. In contrast, PC1, which stands for the meridional shift of PJ, is well connected to the SH intensity but lacks connection with pressure gradients at sea level. Both PC time series are connected with meridional wind shears substantially, and PC2 displays better correlation with the East Asian trough index. Therefore, PC2 can reflect previous common measurements of EAWM variability using a single index to a larger extent than PC1. Given the large meridional extent of EAWM, a single index could not differentiate between middle-to-low- and middle-to-high-latitude circulation anomalies, so the present study will further check the potential of the two modes for capturing different features over the northern and southern East Asian areas.

Regressed patterns of meteorological variables such as SLP, surface temperature, and surface wind on the two PC time series are shown in Fig. 3. The two patterns show distinct surface responses to the concurrent variation of upper-level winds. For the PC1-related pattern, there is anomalous cold surface air in the western and central Siberian region, while for the EOF2 mode prominent cold conditions are found over northern and eastern China, Korea Peninsula, Japan, the East China Sea, and the South China Sea, and warm conditions appear over northern Russia. The two surface air temperature regression patterns associated with upper-level jet variability depict the northern and southern EAWM modes defined by Wang et al. (2010). A salient SLP anomaly occurs over the northern Eurasian continent associated with PC1, while the PC2 regression pattern features an intensified SH, as well as enhanced pressure gradients, indicating a typical sea level pressure pattern of a strong EAWM as revealed by many previous studies. Northerly surface wind anomalies appear over the northern Eurasian continent (north of 55°N) in Fig. 3a, whereas for PC2 northerly wind anomalies extend along the East Asian coast, corresponding to the enhanced pressure gradients there (Fig. 3b). Furthermore, a comparison between the PC time series and the two EAWM modes defined by Wang et al. (2010) shows that PC1 and PC2 are well related to the northern and southern EAWM modes, respectively (Table 1), with the correlation coefficients significant at 99.9% confidence level.

<table>
<thead>
<tr>
<th>2-m air temp</th>
<th>Wang et al. (2010)</th>
<th>SLP</th>
<th>300 hPa</th>
<th>500 hPa</th>
<th>850 hPa</th>
<th>Integrated</th>
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<tbody>
<tr>
<td>PC1</td>
<td>0.763</td>
<td>0.071</td>
<td>0.569</td>
<td>0.024</td>
<td>0.671</td>
<td>0.541</td>
</tr>
<tr>
<td>PC2</td>
<td>0.099</td>
<td>0.840</td>
<td>0.559</td>
<td>0.656</td>
<td>0.491</td>
<td>0.612</td>
</tr>
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Table 1. Correlation coefficients between the two PC time series and various EAWM indices. Values in boldface and italic significantly exceed the confidence level of 99% and 95%, respectively.
The relationship between PC1 and PC2 and the EAWM variability can be confirmed by examining the interdecadal change of EAWM. It has been noticed that EAWM had a notable reduction in the mid-1980s and reamplification in the mid or early 2000s (S.-S. Lee et al. 2013; Wang and Chen 2014). Therefore, as we discussed in the previous section, the interdecadal change of PC1 and PC2 around 1985 (Fig. 2) is consistent with the reduction of the EAWM. Furthermore, the transition of PC1 in the early 2000s is also coincident with reamplification of the EAWM in recent years.

According to the above analysis, the meridional displacement of PJ is connected with the cold conditions in northern East Asia. On the other hand, the out-of-phase relationship in the intensity between TSJ and PJ modes is well linked to the EAWM variability, and can notably reflect the low-level air temperature anomaly in the southern part of East Asia. Thus, the two principal jets’ variation modes can depict the cold condition of northern and southern EAWM modes.

5. Three-dimensional structure of the EAWM in association with the leading variation modes of jets

In this section, we perform composite analyses in terms of PC1 and PC2 to examine the three-dimensional structure of EAWM. Based on the plus or minus one standard deviation of the two PC indices, we obtain seven (six) positive (negative) EOF1 years, and six (five) positive (negative) EOF2 cases during the period of 1979–2014. Table 2 lists the selected years for the two leading modes based on this criterion.

Figure 4 show composite difference maps of the 500-hPa geopotential height and SLP between positive and negative PC1 according to the selected years listed in Table 2. Figure 4a features opposite geopotential height anomalies centered around 40°N at 500 hPa. Negative geopotential height is located around the Lake Baikal region, implying that the northern part of the East Asian trough gets enhanced and exhibits a westward shift (Fig. 4a) during the positive EOF1 case. Meanwhile, a substantial anomalous positive geopotential height occupies the polar region, resulting in weakened polar vortex at 500 hPa. At lower levels, a gigantic anomalous positive SLP dominates the entire northern Eurasian continent, suggesting that the SH expands northwestward in this case (Fig. 4b). Note that in Fig. 4b there is a salient pair of anomalous negative pressures over the western Pacific, one in the midlatitudes and the other near the equator. The midlatitude one is located on the western part of the AL, which substantially reduces the land–ocean pressure gradient. The twin negative geopotential height anomalies resemble changes in the western North Pacific (WNP) anticyclone associated with strong ENSO events as found by Wang et al. (2000; see their Fig. 5a). The twin anomalous cyclones (negative geopotential height anomalies) are reasonable

<table>
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<tr>
<th>Type of years</th>
<th>Selected years</th>
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because in this study Fig. 4a is derived by the difference between positive and negative PC1. Therefore, our EOF1 may be induced by ENSO, which we will further discuss in the next section. Additionally, composite figures of zonal wind anomalies at 300 hPa are displayed in the next section (see Fig. 8), which exhibits accelerated (decelerated) wind in the south (north) of the PJ, indicating southward migration of PJ during the positive EOF1 case, and vice versa.

Figure 5 shows composite difference maps of variables at different levels between positive and negative EOF2. At 500 hPa, there is a wavelike anomaly pattern extending from the western Barents Sea downstream to East Asia, somewhat analogous to the Eurasian teleconnection (EU) pattern (Wallace and Gutzler 1981; Barnston and Livezey 1987). The correlation coefficient between PC2 and the EU index defined by Wallace and Gutzler (1981) is 0.60, which is statistically significant at 99% confidence level. Since the EU pattern is known as a major mode of low-frequency variability that dominates the circulation anomalies in Eurasia region in winter, the anomaly pattern in Fig. 5a implies that the EOF2 is probably linked to atmospheric wave activities. The elongated negative geopotential height anomaly over the midlatitude region (30°–50°N) in Fig. 5a is associated with the enhanced East Asian trough during positive PC2 years. For the sea level pressure field, positive anomalies occur in the Siberian high region (Fig. 5b). Meanwhile, over the Pacific Ocean the AL migrates southward due to the negative pressure anomaly in the south (40°N, 170°E) and positive pressure anomaly in the north (60°N, 180°E), which enhances the pressure gradients over the southern part of East Asia. In the upper level the zonal wind is reduced over the PJ region for positive PC2 cases, and the westerly wind anomalies appear to the south of Tibetan Plateau and extend farther northeastward to the coastal region, implying a weakened PJ and strengthened TSJ (see Fig. 12).

6. Possible reasons for the linkage between the jets’ variation modes and EAWM

The influencing factors of the EAWM and EAJS have been studied extensively, and it is believed that EAWM
variabilities are influenced by large-scale atmospheric and oceanic processes and their interactions. The Arctic Oscillation (AO) (Wu and Huang 1999; Thompson and Wallace 1998, 2000; Gong et al. 2001; Wu and Wang 2002; Chen et al. 2013), ENSO (Li 1989; Tomita and Yasunari 1996; Zhang et al. 1996; Chen et al. 2000; Wang et al. 2000; Chen et al. 2013), and snow cover over Eurasian continent (Watanabe and Nitta 1999; Gong et al. 2003; Jhun and Lee 2004; Wang et al. 2010) are considered as important influencing factors of winter climate over Asian and Eurasian continents. Besides, planetary waves are found to modulate EAWM variability on an interannual time scale (Chen et al. 2005; Takaya and Nakamura 2005). Simultaneously, EAJS variability is also affected by factors such as SST over western North Pacific (Yang et al. 2002), the anomalous snow cover over the Eurasian region (Chen and Sun 2003), as well as the internal atmospheric dynamical processes via positive feedback associated with stationary or synoptic transient eddy activity (STEA) (Klein 1983; Ren and Zhang 2007). Thus, both external forcings and atmospheric internal dynamics play important roles in connecting the jets’ variability with the EAWM. In this section, we intend to examine the linkage between the jets’ variation modes and the EAWM from the perspective of both external forcings and atmospheric wave activities.

a. External forcings associated with PJ meridional migration

1) SST ANOMALIES

The relationship between ENSO and EAWM variation was documented in previous studies (Webster and Yang 1992; Zhang et al. 1996; Lau and Nath 2007). Zhang et al. (1996) revealed that EAWM tends to be weaker (stronger) during the mature phase of El Niño (La Niña). Wang et al. (2010) and Chen et al. (2014a) found that the strong southern EAWM mode is associated with La Niña–like SSTs in the equatorial Pacific. For the northern mode (PC1), the correlation coefficient with the simultaneous winter and previous autumn Niño-3.4 index is −0.55 and −0.40, respectively. Figure 6b indicates that when EOF1 is in a positive phase, the dominant feature in the simultaneous winter is the negative SST anomalies in the tropical eastern Pacific, resembling the typical mature phase of La Niña. The SST anomaly pattern is similar to mega-ENSO (Wang et al. 2013), which involves interannual and multidecadal variations of the Pacific basinwide SST variability. This typical ENSO signal could be traced back to the previous autumn (Fig. 6a). How can tropical SST anomalies affect the meridional migration of the PJ? As shown by Wang et al. (2000), a giant cyclonic anomaly resides over Southeast Asian landmass in composite maps of mid- and upper-tropospheric streamfunction anomalies for warm ENSO events (El Niño) [refer to Figs. 5b,c of Wang et al. (2000) for details]. Correspondingly, the anomalous easterly wind along the northern flank of the Southeast Asian low (30°–40°N) would weaken the westerly flow to the south of the PJ. During a La Niña episode, atmospheric circulation anomalies show an anticyclonic pattern over East Asia, favoring an equatorward shift of the PJ. In association with atmospheric circulation anomaly, the meridional shift of baroclinicity is also manifested, which will be discussed next.

As shown in Fig. 4b, two negative SLP anomalies (anomalous cyclone) exist over the western Pacific, with the southern one located at the Philippine Sea and the northern one over the Kuroshio Extension. Wang et al. (2000) have elucidated that the WNP anticyclone is a key system that bridges the eastern-central Pacific warming and the EAWM. In Fig. 4b, the pair of WNP cyclones appears as a Rossby wave response (Gill 1980)

![Fig. 6. Correlation coefficient map between PC1 and SST in (a) previous autumn and (b) winter. Black dots represent the region with correlation significant at 99% confidence level.](http://journals.ametsoc.org/jcli/article-pdf/28/22/9013/4051077/jcli-d-15-0160_1.pdf)
The existence of WNP cyclones leads the AL to migrate westward and results in an increased zonal land–sea pressure gradient.

Although many studies have indicated that ENSO plays an important role in regulating the interannual variability of the EAWM (Zhang et al. 1996; Wang et al. 2010; Lee et al. 2013; Yang and Lu 2014), other studies have also suggested that the EAWM–ENSO relationship is complicated (Wang and He 2012; He and Wang 2013), and its influence on the major variability modes of EAWM may vary on interdecadal time scale (Lee et al. 2013). In this study, we found ENSO plays an important role in the northern EAWM mode variability.

2) ARCTIC SEA ICE ANOMALIES

Arctic sea ice is also closely related to EAWM variability. Studies reveal that reduced autumn sea ice over the Pacific region of the Arctic would favor a strong EAWM and cold conditions (Honda et al. 2009; Wu et al. 2011). The SIC anomalies over the western and eastern Arctic sections may have opposite impacts on EAWM variability (Chen et al. 2014b). In Fig. 7, the correlation map between the previous autumn SIC anomalies and PC1 indicates that enhanced SIC over the western Arctic area (0°–150°W) and reduced SIC over the eastern Arctic area (30°E–150°W) are both related to the cold winter in northern East Asia. More specifically, reduced sea ice anomalies over Barents–Kara Seas (40°–90°E) are more closely linked to the cold conditions over northern East Asia (Fig. 7).

Since EOF1 is associated with meridional shift of PJ, which is driven by the midlatitude baroclinic eddies, it is necessary to examine atmospheric baroclinicity in the lower troposphere. We further compute the Eady growth rate at 850 hPa, which can be used to measure the atmospheric baroclinicity (Eady 1949; Hoskins and Valdes 1990). The Eady growth rate is defined as the following formula:

$$\sigma = 0.31 \left( \frac{f}{N} \right) \frac{dU}{dz},$$

where $f$ denotes the Coriolis parameter, and $N$ denotes the Brunt–Väisälä frequency, which describes a buoyancy oscillation (inverse seconds). When PC1 is positive, the low-level baroclinicity at 850 hPa is reduced around 50°–70°N and increased around 30°–50°N (Fig. 8a). Therefore, the growth of baroclinic eddies around the PJ region favors the upper-level zonal wind anomaly. In the cold winter of the northern East Asia, with suppressed lower-level baroclinic eddies at the poleward side and increased anomalous baroclinicity at the equatorward side, the main body of PJ tends to shift southward. On the contrary, the PJ shifts northward during warm winters over northern East Asia (Fig. 8b).

Inoue et al. (2012) indicate that diminished sea ice in the Barents–Kara–Laptev Seas (15°–135°E) could induce remarkable weakening baroclinicity from the eastern Greenland coast (20°W) to the Kara Sea (60°–100°E), which shows some consistency with our aforementioned low-level atmospheric baroclinicity change in association with EOF1. The reduced baroclinicity is attributed to SIC anomaly–induced warm condition over the northern Barents Sea and the associated weak SST gradient (Inoue et al. 2012). Comparing to Fig. 4a in Inoue et al. (2012), Fig. 8a shows suppressed lower-level baroclinic eddies over a southward area (50°–70°N), which would weaken the upper-level zonal wind. Inoue et al. (2012) further proved that changes in baroclinicity variability would lead to a northward shift of the cyclone tracks, resulting in a positive SLP anomaly over the Siberian coast. In agreement with this proposed mechanism, our study finds concurrent changes in low-level baroclinicity and a positive SLP anomaly over an extensive area in northern Siberia (Fig. 4a). Thus an amplified SH would bring cold air over northern Asia through enhanced northerlies.

The above analysis shows that both SST (ENSO) and Arctic sea ice anomalies are related to EOF1, and these two signals even appear in the previous autumn. Since
Chen et al. (2014b) pointed out that the autumn Arctic SIC anomalies have no large concurrent SST anomalies on interannual time scales, we propose that these two external forcings act as independent signal in influencing the middle-to-high-latitude climate variability. La Niña (El Niño) modulates PJ through exerting notable anticyclone (cyclone) over East Asia in middle and upper troposphere. On the other hand, Arctic sea ice anomalies may induce low-level anomalous baroclinicity. When cold phase of ENSO (La Niña) develops in the tropics and/or sea ice in the eastern Arctic is reduced, the main body of PJ would shift southward. Meanwhile, the SH would migrate northward and the northern part of the East Asian trough would be strengthened; thus, the associated enhanced northerly wind at the surface leads to a cold winter in northern East Asia.

b. Atmospheric wave activities associated with concurrent variation of PJ and TSJ

The above analysis indicates that the meridional shift of PJ is probably linked to the interaction between the tropical and middle-to-high-latitude systems. Similar correlation analyses are performed for the concurrent variation mode (Fig. 9). During the autumn prior to cold winter in southern East Asia, pronounced cooling is observed over the central and eastern Pacific, which persists through the following winter. During winter, SSTs over the north Indian Ocean show significant negative correlation with PC2 (Fig. 9b). In their paper, J. Lee et al. (2013) indicate that the north Indian Ocean SST shows a noteworthy relationship with the southern EAWM mode, which is consistent with our result. Since tropical Indian Ocean SST anomalies in the autumn could lead to a deepening of southern part of East Asia trough (Wang et al. 2010), our result further shows that the winter north Indian Ocean SST is also closely related to the enhancement of southern part of the East Asian trough (Fig. 5a). Comparing with EOF1, SST anomalies in the Pacific associated with EOF2 are more locally confined, and the pattern resembles central Pacific ENSO or ENSO Modoki (Ashok et al. 2007). Unlike EOF1, there is no significant correlation visible between SIC from the polar region and EOF2 (figure not shown). Nonetheless, the SST signal in the previous autumn
implies potential predictability of southern mode of the EAWM.

Although the precise mechanism responsible for the above linkage between SST forcing and EAWM still remains unclear and deserves further numerical study, it is noted that external forcings may generate EU-like patterns or upper-tropospheric planetary wave modulations, which are closely related to the lower troposphere anomalous monsoon activity (Takaya and Nakamura 2013). Based on the three-dimensional structure of the EOF2 mode, which is characterized by wavelike geopotential height anomaly at 500 hPa (Fig. 5a), and the close relationship with large-scale thermal contrast between land and oceans, it is worth examining the anomalous atmospheric wave activity related to EOF2. We present the composite difference of geopotential height and the corresponding wave activity flux at 250 hPa defined by Takaya and Nakamura (2001). Figure 10 features a global stationary wave train pattern with eastward fluxes. Over the Eastern Hemisphere, salient wave activity fluxes extend eastward from northern Africa (30°N, 20°E) to East Asia along the subtropical jet. This middle-to-low-latitude wave train is characterized by negative geopotential height anomalies over northern Africa, the Tibetan Plateau, and Japan and a positive one over Arabia. Apart from the subtropical teleconnection, another wave train propagates from west of the Barents Sea southeastward to northern Asia and farther southeastward into Japan. Both pathways of stationary Rossby waves are associated with circulation anomalies over the East Asian landmass region, with positive height anomalies (anomalous anticyclone) over northern Asia and negative height anomalies (anomalous cyclone) over the Tibetan Plateau. The zonal winds are decreased to the north (south) of the anomalous anticyclone (cyclone) over Asia, corresponding to the weakened PJ (Fig. 11a); meanwhile, the westerly wind would be enhanced in the south of anomalous anticyclone (over Tibetan Plateau), which is related to the intensified TSJ.
The baroclinic eddies reinforce the zonal wind anomalies in the Northern Hemisphere (Lorenz and Hartmann 2003), and the transient eddy forcing may play a critical role in the variation of upper-level jet streams. Therefore, we further display the composite difference of STEA anomalies associated with EOF2. STEA can be measured by the eddy kinetic energy $K_e = 0.5(\overline{u'^2} + \overline{v'^2})$. Also, the horizontal Eliassen–Palm vector, defined as $\mathbf{E} = (\overline{u'^2} - \overline{u'^2}, -\overline{u'v'})$, is calculated at the 200-hPa level for each winter. In the above equations, $u$ and $v$ denote the zonal and meridional wind velocities, respectively, the primes denote the 2.5–8-day perturbations, and overbars represent temporal averaging during winter. The divergence (convergence) of $E$ corresponds to a forcing on the large-scale horizontal circulation via increasing (decreasing) the mean westerly flow (Hoskins et al. 1983) and therefore can be used to measure the STEA-induced mean flow changes.

Figure 12a shows opposite STEA anomalies over the region to the north and south of Tibetan Plateau, which is associated with the out-of-phase relationship in the intensity between the TSJ and PJ (Figs. 11a, b). The significant reduced STEA to the north of 40°N in the composite difference field is induced by the decreased anomalous baroclinicity over the PJ region (Fig. 11a; see also Fig. 11b, but for the opposite anomaly over the PJ region). The growth of baroclinic eddies along the eddy-driven jet is significantly suppressed, corresponding to the weakened PJ. In contrast, the low-level baroclinicity at 850 hPa is increased over the TSJ section, which favors the enhanced TSJ.

The composite difference of divergence of $E$ is displayed in Fig. 12b to quantify eddy-induced mean flow change due to barotropic processes. Notable convergence of $E$ is located over the PJ region around 50°N, indicating energy conversion from the mean flow to the STEA, which reduces the intensity of PJ. Meanwhile, divergence of $E$ is located to the south of Tibetan Plateau, as well as over East China Sea, which leads to the acceleration of TSJ and part of OSJ over the coastal water of East China. Therefore, STEA anomalies are linked to the out-of-phase relationship in the intensity between TSJ and PJ through convergence and divergence of $E$.

7. Summary and further discussion

In this study, we emphasized the necessity of separating the PJ and SJ when examining the relationship between jet variability and EAWM. It is commonly stated that the SJ shows an in-phase relationship with the EAWM, while in this study the PJ is examined in detail and is found to be well linked to EAWM variability. The PJ modulates EAWM variability through its shift in meridional position and its concurrent variation with the TSJ in intensity. The main results are as follows.

The variability of zonal-mean zonal wind averaged between 70° and 120°E is analyzed using an EOF analysis method. The leading variation modes of the jets feature meridional displacement of the PJ (EOF1) and out-of-phase variation in the intensity of the PJ and TSJ (EOF2). These leading two principal variation modes are found to be well related to EAWM variability with large meridional differences. EOF1 is connected with cold conditions in northern East Asia, and EOF2 can notably reflect the low-level air temperature anomaly in southern part of East Asia. PC2 shows a close connection with other traditional EAWM indices. Thus, the principal variation modes of the jets can depict the EAWM in both northern and southern East Asia.

Major climate patterns associated with the two jet variability modes are different from each other. When the PJ migrates southward, the EAWM circulation
system shifts northwestward, and the northern part of East Asian trough is enhanced and exhibits westward shift. At low levels, the SH expands northwestward, facilitating the intrusion of cold air into northern East Asia. On the other hand, the configuration of the intensified TSJ and weakened PJ is linked to cold winter in southern East Asia. At the 500-hPa level, the geopotential height anomalies feature a wavelike anomaly pattern extending from the western Barents Sea downstream to East Asia. The enhanced SH and the southward shift of the AL dominate the sea level pressure anomalies, demonstrating a typical intensified EAWM pattern.

External forcings such as SST and SIC and internal atmospheric dynamical processes are further analyzed to examine the linkage between the dominant jet variation modes and EAWM variability. Results indicate the predictability of EOF1, with anomalous signals of the tropical SST (ENSO) and Arctic sea ice appearing in the previous autumn. These two external forcings act as an independent signal in influencing the middle-to-high-latitude climate variability. When the cold phase of ENSO (La Niña) develops in the tropics, and sea ice in the eastern Arctic (Barents–Kara Seas) is reduced, their combined influence will contribute to suppressed lower-level baroclinic eddies at the poleward side and increased anomalous baroclinicity at the equatorward side. Concurrently, La Niña–related anticyclonic anomalies appear over East Asia and favor enhanced zonal wind to the south of the PJ. Therefore, the main body of the PJ would shift southward, and meanwhile other EAWM components like the SH and the East Asian trough would migrate northwestward and westward, respectively, leading to the cold winter in northern East Asia. The second mode also shows some SST variability signals over the central and eastern Pacific Ocean in the previous autumn and SST anomaly over the northern Indian Ocean in winter, inducting the potential predictability of southern EAWM mode. The stationary Rossby waves over the Eastern Hemisphere modulate the circulation anomalies over East Asia through the eastward propagation of subtropical and middle-to-high-latitude wave trains, producing anomalous anticyclones over northern Asia and anomalous cyclones over the Tibetan Plateau, and therefore are associated with the weakened PJ and the intensified TSJ. Meanwhile STEA anomalies are linked to the out-of-phase relationship in the intensity between TSJ and PJ through convergence and divergence of E.

In this study we have discussed the important role of the PJ in affecting EAWM variability due to the north–south shifts in the meridional position and out-of-phase relationship in intensity with TSJ. Another interesting phenomenon is that the intensity of the PJ is also negatively correlated with the oceanic subtropical jet (OSJ). From the composite zonal wind anomalies in Fig. 11, it is clear that the intensified (decreased) subtropical zonal winds not only exist over the southern area of Tibetan Plateau but also extend northeastward along to the western Pacific Ocean, suggesting the enhancement (weakening) of the OSJ. The out-of-phase relationship between the OSJ and PJ has been observed and discussed in terms of its influence on winter climate (Liao and Zhang 2013). A composite analysis (equivalent to the method used to create Fig. 4) based on the antiphase relationship in the intensity between OSJ and PJ (figure not shown) shows that the intensified OSJ and weakened PJ induce a strong EAWM, characterized by strengthened northerly wind over East Asia especially along the East Asian coast and cooler surface temperature over the central East Asian region south of 40°N, a fairly good resemblance of the southern EAWM mode proposed by Wang et al. (2010; refer to their Fig. 6c). This implies that the OSJ can also influence variation of the southern EAWM mode, for example, through its concurrent variation with PJ. Therefore, it is necessary to further investigate the effects of concurrent variation of the three jets on the middle-to-low-latitude EAWM variability.

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