Modulation of the Intraseasonal Variability of Pacific–Japan Pattern by ENSO

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ABSTRACT

This study investigates how the El Niño–Southern Oscillation (ENSO) modulates the intraseasonal variability (ISV) of Pacific–Japan (PJ) teleconnection pattern. The PJ index during boreal summer is constructed from the empirical orthogonal function (EOF) of the 850-hPa zonal wind (U850) anomalies. Distinct periods of the PJ index are found during El Niño and La Niña summers. Although ISV of the PJ pattern is significant during 10–25 days for both types of summers, it peaks on Days 30 and 60 in El Niño and La Niña summers respectively. During El Niño summers, the 30-day ISV of PJ pattern is related to the northwestward propagating intraseasonal oscillation (ISO) over the western North Pacific (WNP), which is originated from the tropical Indian Ocean (IO). During La Niña summers, the 60-day ISV of PJ pattern is related to the northeastward propagating ISO from the tropical IO. The low-frequency ISV modes in both El Niño and La Niña summers are closely related to the boreal summer ISO (BSISO), and the high-frequency ISV modes over WNP are related to the quasi-biweekly oscillation. The underlying mechanisms for these different evolutions are also discussed.

Key words: Pacific–Japan (PJ) pattern, El Niño–Southern Oscillation (ENSO), intraseasonal variability (ISV), intraseasonal oscillation (ISO), intraseasonal timescale, low-frequency ISV mode, boreal summer ISO

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1. Introduction

The Pacific–Japan (PJ) teleconnection pattern (Nitta, 1987), also named the East Asia–Pacific (EAP) pattern (Huang and Sun, 1992), is a correlation between the above-normal (below-normal) convective activity over the western tropical Pacific and weaker-than-normal (stronger-than-normal) Meiyu frontal rainfall in East Asia. It displays alternating cyclonic and anticyclonic anomalies in the meridional direction in the lower troposphere, significantly influencing the summer time atmospheric circulation and climate anomalies in East Asia (Huang and Li, 1988; Nitta and Hu, 1996; Wakabayashi and Kawamura, 2004; Kosaka and Nakamura, 2006). The PJ pattern is closely related to the East Asian summer monsoon (EASM). Studies have also shown that the PJ pattern is closely linked to changes of the western North Pacific (WNP) monsoon trough, subtropical high, Meiyu trough, and Okhotsk high in the EASM areas (Huang and Sun, 1992; Wu et al., 2013; Li et al., 2016; Tao et al., 2017). The PJ pattern also has striking impacts on the summer temperature and precipitation in China. Precipitation anomalies in the middle and lower reaches of the Yangtze River basin are closely associated with the PJ pattern (Hsu and Lin, 2007; Chen and Zhai, 2015; Li et al., 2016).

The PJ pattern at the interannual timescale has been extensively studied. A general understanding is that the PJ pattern is forced by anomalous heating associated with the anomalous sea surface temperature (SST) in the Philippine Sea (Nitta, 1987; Nitta and Hu, 1996), and with convective heating over the tropical WNP, which can excite Rossby waves to propagate northward to the midlatitudes (Kosaka and Nakamura, 2006). The Silk Road Pattern propagating along the waveguide of the subtropical jet stream has further influences on the variability of Bonin high, which can lead to the formation of

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The PJ pattern (Hsu and Lin, 2007). The PJ pattern may also result from the propagation of barotropic Rossby wave train generated by typhoon activity (Yamada and Kawamura, 2007). On the other hand, the PJ pattern may be considered as a moist dynamic mode, which can be greatly excited in the zonally varying baroclinic mean flow associated with the EASM under an efficient self-sustaining mechanism (Kosaka and Nakamura, 2006, 2008; Kosaka et al., 2011). In addition, the interaction between the anomalous summer precipitation in East Asia and atmospheric circulation plays an important role in the maintenance of the PJ teleconnection (Lu and Lin, 2009). The impact of anomalous summer precipitation on the atmospheric circulation cannot be ignored. The PJ pattern at the interdecadal timescale was also investigated (Wu et al., 2016), which is driven by negative anomalous convective heating over the tropical WNP that is associated with the interdecadal Pacific oscillation (IPO) and interdecadal Indian Ocean (IO) basin mode. However, many of these previous efforts mainly focused on the interannual and interdecadal variability of the PJ pattern.

Research also revealed that strong intraseasonal variability (ISV) exists in the PJ pattern (Wu et al., 2013; Li et al., 2014; Wang et al., 2016; Xie et al., 2016; Li et al., 2018). The ISV in the EASM defined by the leading empirical orthogonal function (EOF) mode of the 850-hPa zonal wind (U850) anomalies during 1979–2010 is dominated by the PJ pattern of 25–60 days, and its circulation anomalies exhibit a meridional wave-like distribution with alternate cyclonic and anticyclonic anomalies (Wu et al., 2013). The ISV of the PJ pattern defined by the difference in the 850-hPa geopotential height anomalies between eastern Taiwan Island and eastern Japan is dominated by 10–50-day oscillations, which has great impacts on the synoptic-scale variability (SSV) in the WNP (Li et al., 2014). By applying EOF to the normalized 500-hPa zonal wind (U500) anomalies over East Asia for 1979–2012, Wang et al. (2016) proposed that the PJ pattern peaks during 30–60 and 10–20 days, and the leading EOF mode is characterized by evident anomalous centers with alternating signs (Wang et al., 2016). In addition, the PJ pattern defined by the difference in the normalized 500-hPa geopotential height anomalies between the sum of the Sea of Okhotsk and western Pacific (WP) as well as the midlatitude of East Asia exhibits remarkable 10–30- and 30–60-day oscillations based on an ensemble empirical mode decomposition (EEMD) method (Li et al., 2016). The studies mentioned above introduce characteristics of the PJ pattern at the intraseasonal timescale.
possible mechanisms corresponding to different ENSO phases are investigated. Discussion and conclusions are given in Section 5.

2. Data and methods

In this study, we use the daily ECMWF reanalysis data (Dee et al., 2011), which are available over a 40-yr period from 1979 to 2018, including the wind and precipitation fields at a resolution of 2.5° × 2.5°. Another daily precipitation dataset is the Global Precipitation Climatology Project (GPCP) version 1.2 dataset (Huffman et al., 1997) provided by the US NOAA. The GPCP precipitation has a resolution of 1° × 1° and is available from October 1996 to October 2015. We also use the monthly mean SST from the Extended Reconstructed SST version 5 (ERSST.v5) dataset developed by NOAA (Smith et al., 2008) with a resolution of 2.5° × 2.5° for 1979–2018, and the daily gridded data of the NOAA interpolated outgoing longwave radiation (OLR; Liebmann and Smith, 1996) with a resolution of 2.5° × 2.5° for 1979–2018.

The interannual component of PJ pattern can be illustrated by applying EOF to June–July–August (JJA) averaged zonal wind anomalies in boreal summer in the EASM region (0°–60°N, 100°–160°E) for the study period. The interannual component of zonal wind anomalies is retained via subtracting the linear trend at each grid point and the 9-yr running means in boreal summer. The EOF method is also utilized to analyze the daily zonal wind anomalies at the intraseasonal timescale in boreal summer in the EASM region during 1979–2018 to obtain the intraseasonal component of PJ pattern. To isolate the intraseasonal signal of zonal wind anomalies, the slow annual cycle (mean and first three harmonics of the climatological annual variation) and effect of the interannual variability are removed by subtracting the running mean of 120 days, and a 5-day running mean is applied to remove synoptic fluctuations (Wheeler and Hendon, 2004). The first principal component (PC) time series of the EOF mode from 1979 to 2018, which is considered as the PJ pattern index, is thus obtained.

To extract ISV of the PJ pattern during an ENSO phase, ENSO events are categorized by using the Niño 3.4 (5°S–5°N, 170°–120°W) SST anomalies during 1979–2018. Based on the June–September mean Niño 3.4 index, we define El Niño and La Niña events as follows: it is an El Niño and La Niña event above 0.5°C and below −0.5°C respectively. Based on the above definition, 1982, 1987, 1991, 1997, 2002, 2009, and 2015 are El Niño years while 1985, 1988, 1999, 2000, and 2010 are selected as La Niña years. By applying the EOF method, modes and PC time series of both El Niño and La Niña years are obtained. In the following study, the first PC (PC1) time series are considered as the PJ index. In order to investigate the statistically significant and dominant periodicity of each index, the spectral analysis is applied on the two kinds of daily PJ index. Due to the high autocorrelations between consecutive daily values, the effective degrees of freedom are calculated for each variable at each grid during an ENSO phase by using Chen’s method (Chen, 1982).

3. Dominant periodicity of ISV during El Niño and La Niña summers

EOF is employed to analyze the JJA averaged zonal wind at 850, 500, and 200 hPa (U200) to obtain the interannual PJ pattern. In addition, for the intraseasonal PJ pattern, EOF is applied to the daily U850 anomalies in boreal summer. Many previous studies focused on JJA, but through calculating the monthly mean of absolute value of projection coefficients obtained by projecting the daily U850 anomalies over the year onto the interannual PJ pattern, which is considered as the leading EOF mode of U850 anomalies in JJA (Fig. 1), we find that the value in September (0.94) is even larger than that in June (0.89). Therefore, we choose four months (June–July–August–September, or JJAS) to obtain the intraseasonal component of the PJ pattern.

The interannual and intraseasonal PJ patterns of leading EOF modes of U200, U500, and U850 anomalies in boreal summer for 1979–2018 are presented. The lead-
ing modes are statistically distinguishable from higher modes according to the criteria of North et al. (1982). There appear alternately positive and negative anomalous circulation centers over the Okhotsk Sea, vicinity of Japan, and the Philippines, which resemble the PJ pattern discussed by Nitta (1987). It can be seen that there exists an anticyclonic anomaly over the subtropical WNP and a cyclonic anomaly over midlatitude East Asia on the interannual and intraseasonal timescales (Figs. 2a–c). However, there are some differences between the interannual and intraseasonal timescales. On the interannual timescale, the low-latitude easterly center is located in the WNP, which is far more eastward and southward than that on the intraseasonal timescale (Fig. 2a). Figure 2b illustrates that the easterly is stronger at the midlatitude, and the westerly wind at the lower latitudes is weakened on both timescales. The PJ pattern is barotropic at the mid-to-high latitudes, and is baroclinic at the low latitudes. Due to the presence of westerly jets, high-latitude easterlies are extremely strong in Fig. 2c. Figure 2d shows the power spectra of PC1 of U850, U500, and U200 at the intraseasonal timescale. The spectral peak is prominent during 10–70 days for the intraseasonal timescale. It is more obvious at low frequency for the 850-hPa result, while it is closer to high frequency at 200 hPa due to more mid-to-high latitude signals in the upper troposphere.

To focus on the impact of interannually varying background state related to ENSO on ISV of the PJ pattern, we apply the EOF analysis on U850 anomalies in JJAS over the EASM region during seven El Niño years and five La Niña years, respectively. Percentage variances for the first four modes are 21.4%, 11.4%, 9.2%, and 7.9% respectively for El Niño years; while they are 23.6%, 13.9%, 9.0%, and 6.5% for La Niña years. In addition, the first four modes are statistically distinguishable from...
each other according to the rule of North et al. (1982). Figure 3 shows the wind and precipitation regressed on PC1 during El Niño and La Niña summers, respectively. The circulation fields in Figs. 3a, b are also analogous to

Fig. 3. (a, b) Spatial structures of leading EOF modes of U850 anomalies during JJAS for (a) El Niño years (1982, 1987, 1991, 1997, 2002, 2009, and 2015; corresponding to the left panels) and (b) La Niña years (1985, 1988, 1999, 2000, and 2010; corresponding to the right panels). (c–f) The wind (m s$^{-1}$) and precipitation anomalies (mm day$^{-1}$) are regressed on the PC1 time series of Figs. 3a, b. The precipitation data used in (c, d) are from GPCP while those in (e, f) are from the ECMWF reanalysis (ERA) dataset.
those of the PJ pattern. The easterly in the tropics is stronger than the westerly in the midlatitude during El Niño summers (Fig. 3a). The center of the easterly in the tropics in La Niña summers is west of the westerly in the midlatitude (Fig. 3b). Through regression on the wind and precipitation anomalies (Figs. 3c–f), we find that the anticyclonic anomaly is associated with the suppressed precipitation anomalies over the WNP and enhanced rainfall along the Meiyu rainbelt, and La Niña summers experience more prominent precipitation along the Meiyu rainbelt. In summary, ISV of the PJ pattern is found to be ENSO-phase dependent.

To identify the dominant timescale of PC1 during El Niño (La Niña) summers, the mean power spectrum is computed by averaging the individual spectrum over El Niño and La Niña summers respectively (Fig. 4). Based on the 99% confidence test, two frequency bands are identified during both El Niño and La Niña summers, which occur on Days 10–25 and 25–70, respectively. During El Niño summers, peaks are on Days 15 and 30. During La Niña summers, significant spectral peaks are seen on Days 18 and 60. The difference of ISV periodicity between El Niño and La Niña summers is statistically significant.

Figure 5 illustrates temporal evolution patterns (from Day –30 to 0) of the 25–70-day filtered leading ISV modes for El Niño and La Niña years. During El Niño summers, it shows a complete cycle. A part of the negative convection anomaly associated with the ISO originated from the tropical IO on Day –30 propagates northeastward to the Indian monsoon region, and the other part of the signal takes about 15 days to propagate eastward to the WP. The ISO arriving at the WP can take similarly 15 days to move northwestward to the Philippines. In a complete cycle, we can find that the process of shifting from the WP to the Philippines emerges twice. It also shows a complete cycle for the circulation field of the 850-hPa wind anomaly. Note that a cyclonic anomaly first emerges over the North Pacific on Day –24, which is similar to the system revealed in Wang et al. (2016). Then, a tilted tripole pattern of “cyclonic–anticyclonic–cyclonic” emerges across East Asia on Day –18. As time progresses, the tripole pattern of “anticyclonic–cyclonic–anticyclonic” appears on Day –6 over East Asia. The most prominent feature is the strong negative convective anomaly along with the powerful anticyclonic anomaly in the Philippines at the peak phase.

During La Niña summers, the evolution from Day –30 to 0 completes half a cycle because the pattern on Day –30 is nearly similar to that on Day 0, with reversed signs. There appears a tilted dipole pattern with negative convection anomaly over the IO and positive convection anomaly over the Philippines on Day –30. The negative convection anomaly over the IO moves northeastward to the Philippines during the next successive days. The anomaly in the Philippines is enhanced at the peak phase with the prominent precipitation anomaly along the Meiyu rainbelt. The positive OLR anomaly, along with the anticyclonic anomaly, in the Philippines is strengthened at the peak phase.

For the low-frequency PJ pattern, the evolution during El Niño summers is distinct from that during La Niña summers. The propagation cycle during La Niña summers is twice as long as that during El Niño summers. For the propagation direction, a significant difference appears. The low-frequency ISV in El Niño summers is characterized by northwestward propagating negative convective signals over the tropical WP, and it is originated from the tropical IO; while the low-frequency ISV during La Niña summers propagates northeastward from the tropical IO. A significant feature is that the two dipoles over the ISM area and WNP are coupled on Day –12 during El Niño summers.

Figure 6 shows the half cycle (from Day –7 to 0) of OLR and 850-hPa wind anomalies on the 10–25-day frequency band by regressing the filtered variable anomalies on the 10–25-day filtered PJ index during El Niño and La Niña summers respectively. As is illustrated in Fig. 6, a positive OLR anomaly located in the area of 15°–20°N, 160°E–180° appears on Day –7 during El Niño summers, while it first appears on Day –5 during

![Fig. 4.](image)
La Niña summers. Meanwhile, they are enhanced and move westward to the Philippines in the following days. Significantly, a weak anticyclonic anomaly located in the area of 15°–20°N, 160°E–180° first emerges on Day –7, and then moves westward slowly in the following days to form an anticyclonic anomaly in the Philippines at the

Fig. 5. Evolution patterns of the 25–70-day bandpass-filtered OLR anomalies (shading; W m$^{-2}$) and 850-hPa wind anomalies (vector; m s$^{-1}$) regressed on the 25–70-day bandpass-filtered PC1 time series respectively, during El Niño and La Niña summers (from Day –30 to 0). Only regressed OLR and wind anomalies confident at the 95% level by Student’s $t$-test are plotted.
peak phase during El Niño summers. In contrast, during La Niña summers, a weak anticyclonic anomaly forms on Day –3, and then moves westward quickly to form an anticyclonic anomaly in the Philippines at the peak phase. The positive OLR anomaly and anticyclonic anomaly in the peak phase are both weaker than those during El Niño summers. It can be clearly seen from Fig. 6 (left panels) that an anticyclonic anomaly emerges over the North Pacific on Day –5 during El Niño summers, which is similar to the low-frequency evolution in Fig. 5 (left panels), but it does not appear in La Niña summers.

4. Possible mechanisms

As depicted in Section 3, ISO in El Niño and La Niña summers shows two frequency bands, with periods of 10–25 and 25–70 days. But they bear some differences in the low-frequency band; that is, ISO in El Niño and La Niña summers peaks on Day 30 and 60 respectively.

BSISO is a potential factor affecting the intraseasonal PJ pattern. The multivariate EOF (MV-EOF) is usually used to calculate the real time index for MJO (Wheeler and Hendon, 2004) and BSISO (Lee et al., 2013). To study the relationship of ISV and BSISO, correlations
between the PC1 values of BSISO and PJ pattern (Fig. 3) during El Niño and La Niña summers are first calculated, which are –0.88 and –0.86 for El Niño and La Niña summers, respectively. In addition, the spectral analysis of PC1 of BSISO is presented in El Niño and La Niña summers (Fig. 7). The spectral peak is prominent on Day 30 and 60 during El Niño and La Niña summers respectively, which is consistent with the PJ index in these two summers (Fig. 4).

The 25–70-day filtered OLR used to study the evolution process of BSISO is regressed onto ENSO phases (Fig. 8). During El Niño summers, the BSISO initiating from IO can grow; one part propagates northward to the ISM region, and the other part can propagate eastward to the WP. The branch over the WP can propagate northward into the WNP (about 15 days), which is the same as the evolution process of PJ pattern during El Niño summers. During La Niña summers, the BSISO initiates from the IO, and can propagate northeastward to the WNP (about 30 days). From the regression of OLR onto the ENSO phase, we find that both frequency bands of the PJ pattern on ENSO phases are significantly related to BSISO in El Niño and La Niña summers.

The possible mechanism for the difference is probably attributed to the different background fields. El Niño warming in the central and eastern Pacific, which can result in the westerly (easterly) anomalies in the lower (upper) troposphere over WP, leads to an easterly shear anomaly around 150°E (Teng and Wang, 2003; Liu et al., 2016). Compared with El Niño summers, La Niña summers have stronger westerly vertical wind shear anomaly and negative moisture anomaly over the WNP; in addition, stronger positive moisture anomaly also appears over the Meiyu rainbelt and southern part of the MC (Figs. 9a, b). The monsoon trough in La Niña summers is stronger and forms a stronger Meiyu rainbelt. There are IO dipole (IOD)-like SST anomalies in the tropical IO (Figs. 9c, d). The eastward propagation of ISV in El Niño summers will also be suppressed by a positive phase of the IOD mode (Fig. 9c), while in La Niña summers it will be promoted by a negative phase of the IOD mode (Fig. 9d).

The propagation direction of low-frequency PJ pattern during El Niño summers is distinct from that during La Niña summers. Due to the positive boundary layer moisture anomaly in the WNP during El Niño summers, the convective signals originated from the tropical IO can propagate eastward to the WNP, and then propagate northward to the Philippines. On the contrary, during La Niña summers, the ISO initiated from IO can only propagate northeastward to the Philippines without going through the WNP due to the negative moisture anomaly in the WNP.

5. Summary and discussion

Effects of ENSO on the periodicity and spatiotemporal evolution of ISV of the PJ pattern in boreal summer have been studied by using the ECMWF reanalysis data for the period from 1979 to 2018. The PJ index during El Niño and La Niña summers is constructed from EOF of U850 anomalies in El Niño and La Niña years respectively. The power spectral analysis of the index shows a significant difference (Fig. 4). ISOs in El Niño and La Niña summers are dominated by two frequency bands, with periods of 10–25 and 25–70 days, but there exist some differences in the low-frequency band: ISO in El Niño summers peaks on Day 30 while it peaks on Day 60 in La Niña years.

El Niño and La Niña summers exhibit different spatiotemporal evolution patterns of ISO. Originating from the tropical IO 15 days ago, the northwestward propagating signals over the tropical WP are the main feature of the low-frequency ISO mode during El Niño summers. During La Niña summers, the low-frequency ISV propagates northeastward from the tropical IO. The high-frequency ISO modes in El Niño and La Niña summers are similar with the biweekly mode, which is characterized by the convective signals over the WNP propagating westward. The PJ pattern at the low frequency in El Niño and La Niña summers is significantly related to BSISO (Fig. 8).

A schematic diagram for different ISO evolution patterns during different ENSO phases is presented in Fig.
During El Niño summers (Fig. 10a), ISO is originated from IO on Day –30. A part of ISO can propagate northward to the ISM region in 15 days, and the rest can propagate eastward to WP in 15 days; then ISO over WP can take 15 days to propagate northwestward to the Philippines. During La Niña summers (Fig. 10b), the ISO initiated from IO can propagate continuously northeastward to the Philippines in 30 days.

The tropical–extratropical interaction is of great significance for the PJ pattern. Lu et al. (2007) revealed the
relationship between BSISO and midlatitude low-frequency disturbances. A westward-traveling wave train, which appears over the North Pacific, is prior to the convection variability over the Philippines (Lu et al., 2007). The above study by Lu et al. (2007) emphasized the impact of extratropical variability on the tropical convection. Lin et al. (2018) found that the PJ pattern was absent in the extratropics due to very weak circulation anomalies in the mid and high latitudes from multi-model ensemble mean forecasts. Different from the above studies, we concentrate on the influence of tropical convection. Besides, Hsu and Lin (2007) illustrated an asymmetric relationship between the tropical convection and PJ pattern; specifically, the positive phase of PJ pattern tends to have a stronger tropical connection while the negative phase has a stronger extratropical connection. Therefore, the asymmetry of dependence of the low-frequency PJ pattern on ENSO should be considered as an important issue for future investigation.

From the perspective of relationship between the MJO and PJ pattern, Li et al. (2019) proposed that the impact MJO exerts on the PJ pattern at the interannual timescale mainly occurs at 850 hPa and results from changes in the occurrence frequency of MJO. It is noted that the downward branch favors the suppressed convection over WNP during the early MJO phases, which leads to the positive phase of PJ pattern (Li et al., 2019). In terms of the relationship between BSISO and PJ pattern, Wang et al. (2016) proposed that the elongated anomalous convection band located in the Philippines associated with BSISO has a significant impact on the initiation of intraseasonal PJ via Rossby wave propagation (Wang et al., 2016). In this study, we discuss the ISV of the PJ pattern in El Niño and La Niña summers respectively. We find that the PJ pattern at the low frequency in El Niño and La Niña summers is significantly related to BSISO. The distinctive background mean states in El Niño and La Niña summers play important roles in determining the propagation direction of the ISV of the PJ pattern.
However, it remains unclear whether the ENSO-phase-dependent low-frequency PJ pattern has a great impact on extended-range and seasonal predictions or not, which should be considered as an important issue of future research.

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