Relationship between the Boreal Summer Intraseasonal Oscillation and the Pacific-Japan Pattern and Its Interannual Modulations

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Abstract

The relationship between the boreal summer intraseasonal oscillation (BSISO) in the tropics and the summertime tropical-extratropical teleconnection called the Pacific-Japan (PJ) pattern is investigated. The positive correlation between the BSISO and intraseasonal PJ pattern peaks during BSISO phase 8 when the convective center of the BSISO reaches the vicinity of the Philippines. A composite analysis based on the BSISO events shows that intraseasonal responses to the migration of the BSISO extend to the midlatitudes and form circulation anomalies reminiscent of the PJ pattern. During phases 7–8, cyclonic wind anomalies with low-pressure signals drastically intensify north of the Philippines and southeasterly wind anomalies blow into midlatitude East Asia, influencing the summer climate. Other apparent intraseasonal signals in pressure and surface air temperature are found over the midlatitude central Pacific and eastern Eurasia, respectively. The intraseasonal variability in the PJ pattern associated with the BSISO undergoes strong interannual modulations, with enhanced intraseasonal signals in summers of the positive seasonal-mean PJ pattern and suppressed signals in those of the negative PJ pattern. This asymmetry between the positive and negative PJ summers highlights the importance of cross-scale interactions for a better understanding of summer climate in East Asia.

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1. Introduction

During boreal summer, convective activities around the northern Philippines have been known to be associated with circulation anomalies over the midlatitude western North Pacific (WNP), forming a meridional dipole of lower tropospheric circulation anomalies. This tropical-midlatitude teleconnection pattern, called the Pacific-Japan (PJ) pattern, constitutes an integral part of the Pacific-Japan (PJ) pattern, constitutes an integral part of the East Asian summer monsoon and influences the summer climate in East Asia through variations in the subtropical Bonin (Ogasawara) high (e.g., Nitta 1987; Kurihara and Tsuyuki 1987). For example, vigorous convective activities around the Philippines are linked to anticyclonic anomalies over the midlatitude WNP, resulting in hot summers in Japan (Wakabayashi and Kawamura 2004). The PJ pattern has been regarded as a Rossby wave train (e.g., Huang and Sun 1992) or an internal atmospheric mode (e.g., Kosaka and Nakamura 2006; 2010; Hirota and Takahashi 2012), excited by anomalous convective activities around the Philippines. Regarding an interbasin effect on convective activities, anticyclonic anomalies with suppressed convection develop over the tropical WNP through ocean-atmosphere feedback in the Indo-western Pacific region during the post-El Niño summer (e.g., Xie et al. 2009, 2016). Although many previous studies have investigated the mechanism and characteristics of the PJ pattern, it has not been fully elucidated what kind of atmospheric phenomena contribute to the excitation of the PJ pattern since previous studies have focused mainly on the variability of seasonal-mean states. The dominant intraseasonal atmospheric variability in the tropics during boreal summer and winter is called the boreal summer intraseasonal oscillation (BSISO; e.g., Wang and Rui 1990; Lawrence and Webster 2002; Kikuchi et al. 2010, 2012) and the Madden-Julian Oscillation (MJO; e.g., Madden and Julian 1971, 1972), respectively. Whereas the MJO has organized convection propagating eastward around the equator, the BSISO is accompanied only by eastward-propagating convection and influences the convective activities around the Philippines directly. A recent study (Li et al. 2018, 2019) indicated that the primary contribution of the MJO to the interannual variation in the PJ pattern comes from a change in the frequency of MJO phases 6 and 7. While they chose the MJO index rather than the BSISO index, the phase of the MJO was similar to that of the BSISO. The intraseasonal PJ pattern is subject to modulations by the El Niño-Southern Oscillation (Li et al. 2020), and its predictability has been evaluated using climate models (Wu et al. 2015) provided by the Japan Meteorological Agency. Sea level pressure (SLP), surface air temperature (SAT), zonal and meridional winds, and relative vorticity data are used. As a proxy for convective activities associated with the BSISO, daily outgoing longwave radiation (OLR) data derived by the U. S. National Oceanic and Atmospheric Administration (NOAA) on 2.5° × 2.5° grids are used. We focus on the boreal summer season from June to August (JJA) for the 1979–2018 period. To detect intraseasonal signals, a 91-day running-mean daily climatology of the annual modulations have not been fully explored. This study aims to reveal this intraseasonal relationship between the PJ pattern and BSISO, and their modulations with the interannual PJ pattern.

2. Data and methodology

The primary data used in this study are mean-daily reanalysis data recorded four times daily on a 1.25° × 1.25° grid obtained from the Japanese 55-year Reanalysis (JRA55; Kobayashi et al. 2015) provided by the Japan Meteorological Agency. Sea level pressure (SLP), surface air temperature (SAT), zonal and meridional winds, and relative vorticity data are used. As a proxy for convective activities associated with the BSISO, daily outgoing longwave radiation (OLR) data derived by the U. S. National Oceanic and Atmospheric Administration (NOAA) on 2.5° × 2.5° grids are used. We focus on the boreal summer season from June to August (JJA) for the 1979–2018 period. To detect intraseasonal signals, a 91-day running-mean daily climatology of the annual cycle is first removed, and then a 20–100-day bandpass filter is applied to all data.

We apply an empirical orthogonal function (EOF) analysis to either intraseasonal or interannual variability of horizontally smoothed vorticity at 850 hPa over the WNP region (0°–60°N, 106°E–160°E) in JJA to extract the PJ pattern (see Kosaka and Nakamura 2010 for details of the horizontal smoothing). For
Intraseasonal variability, the first mode (EOF1) explains 17.3% of the total variance and is well separated from higher modes based on the criteria by North et al. (1982). The corresponding spatial patterns (Fig. 1) regressed onto the intraseasonal EOF1 feature a meridional dipole of zonally elongated pressure anomalies between the Philippine Sea and midlatitude East Asia, similar to the interannual EOF1 (not shown). Slightly south of the cyclonic anomalies, enhanced convective anomalies spread widely around the Philippine Sea. Signals in the subtropics are generally stronger than in other regions. The structure is consistent with the PJ pattern described in previous studies. The intraseasonal PJ pattern index is defined as the principal component of the intraseasonal EOF1. Note that its polarity is defined in this study so that the positive PJ pattern features cyclonic and anticyclonic circulation anomalies in the tropical and midlatitude lobes, respectively.

This study uses the BSISO index proposed by Kikuchi et al. (2012) based on the extended EOF analysis of intraseasonal OLR variability during boreal summer. The amplitude ($A$) and phases of the BSISO are described by a combination of the first two principal components, hereafter referred to as BPC1 and BPC2 (see Fig. 7 of Kikuchi et al. 2012). A BSISO event in this study is identified when $A \geq 1$ for 15 consecutive days, and the phase of the BSISO is denoted by eight categories.

3. Relationship between the BSISO and intraseasonal PJ pattern

The intraseasonal relationship between the BSISO and PJ pattern is shown by lag correlation analysis (Fig. 2). While the PJ index is not correlated with the overall amplitude of the BSISO index, a strong correlation of the PJ signals with the phases of the BSISO is found. The minimum BPC1 (BPC2) precedes the positive PJ signals by six (16) days. Referring to the composite life cycle of the BSISO in Kikuchi et al. (2012), Fig. 2 shows that the positive (negative) PJ pattern is most active after the center of the BSISO reaches the WNP (the Bay of Bengal) through the Maritime Continent (the central North Pacific). The correlation of the linear combination of BPC1 and BPC2, $BPC2 \times \cos \theta + BPC1 \times \sin \theta$ (following Fig. 7 of Kikuchi et al. 2012), with the PJ index maximizes at $\theta = 155^\circ$ with a value of 0.34, which exceeds the 99% confidence level. These results indicate that the positive PJ pattern peaks during BSISO phase 8 when the center of active convection reaches north of the Philippines and the Philippine Sea. We also calculate the correlation coefficients between the PJ index and BSISO amplitude during phases 1–2, 3–4, 5–6, and 7–8 since the BSISO amplitude data used above do not contain phase information. Although the positive (negative) correlation is highest during phases 7–8 (3–4), the correlation coefficient is 0.12 (~0.10), which is not statistically significant. This result indicates that the amplitude of the BSISO is not a crucial factor in exciting the PJ pattern when the BSISO convection is located around the Philippine Sea whereas the PJ pattern is phase-locked to the BSISO migration.

Figure 3 (left) shows composite intraseasonal OLR and SAT anomalies for the BSISO events from phases 1–2 to 7–8 (see Supplemental Figs. 1 and 2 for the results with each of the eight BSISO phases). Hereafter, the statistical significance of composite anomalies is examined using Student’s t test. In the tropics, a zonally elongated convectively active (suppressed) region forms over the equatorial Indian Ocean in phases 1–2 (5–6), migrates northeastward through the Bay of Bengal and Maritime Continent, and reaches the tropical WNP, consistent with previous studies (e.g., Kikuchi et al. 2012). Intraseasonal responses to the migration of the BSISO are also apparent in the subtropics and even in midlatitudes. Although intraseasonal OLR signals are generally weak in northern midlatitudes, a statistically significant suppression (enhancement) of convection is found east (south) of Japan during phases 1–2. During phases 7–8 (3–4), cyclonic (anticyclonic) wind anomalies with low (high) pressure signals in Fig. 3 (right) drastically
intensify north of the Philippines and form the tropical lobe of the meridional dipole similar to the positive (negative) PJ pattern, consistent with the results of the lag correlation analysis. Although the pressure signal is weak around Japan, its meridional gradient with significant pressure anomalies in the tropics results in anomalous southeasterly winds blowing into midlatitude East Asia during phases 7–8. Furthermore, low- (high-) pressure anomalies with low-level westerly (easterly) wind anomalies on the southern side develop over the midlatitude central Pacific east of 160°E in phases 7–8 (3–4), which may be related to the midlatitude 45-day oscillation that exhibits the largest variability around the jet exit region (Kawamura et al. 1996). Note that in the asymmetric features, the amplitude of pressure anomalies north of the Philippines (the midlatitude central Pacific) is larger in phases 7–8 (3–4) than...
Mid-latitude responses found in the positive PJ years are not fully statistically significant. The lack of a significant difference in the longest duration are found in the positive PJ years and other years, negative PJ years. On the other hand, the strongest amplitude and shortest duration are found in the negative PJ years, which may explain the differences in SAT anomalies through similar intensities of convective activities over the Maritime Continent and the Philippines, which is apparent in the positive PJ years whereas convection weakens in the negative PJ years, despite similar intensities of convective activities over the Maritime Continent in phase 4 in all three composites. Correspondingly, low-pressure anomalies rapidly develop north of the Philippines from phase 5 and evolve into wave train signals from north of the Philippines toward North America during phases 7 in the positive PJ years, whereas convection weakens in the negative PJ years, which may explain the differences in SAT anomalies through meridional advection of warm air. However, further studies are needed to clarify the mechanism of SAT anomalies.

While the strongest convection over the tropical WNP and associated teleconnection are observed in the positive PJ years, the teleconnection of the opposite polarity with convectively suppressed signals over the tropical WNP during phases 8 and 1–3 is also strongest in the positive PJ years. These results highlight that the intraseasonal PJ pattern associated with the BSISO undergoes strong interannual modulations. Intraseasonal signals similar to the PJ pattern are evident in the interannual positive PJ years but rather weak in the interannual negative PJ years. Thus, the intraseasonal BSISO-PJ relationship is asymmetric between the positive and negative phases of the intraseasonal PJ pattern.

A statistical analysis of the BSISO shows that the mean amplitudes (duration in days) of the BSISO events are 1.77 (30.6), 1.44 (28.1), and 1.60 (34.8) in the positive PJ, negative PJ, and other years, respectively. The mean amplitude difference between the positive and negative PJ years and the duration difference between the negative PJ and other years are statistically significant at the 95% confidence level in the two sample Student’s t test. The weakest amplitude and shortest duration are found in the negative PJ years. On the other hand, the strongest amplitude and longest duration are found in the positive PJ years and other years, respectively, although the differences between the two groups are not statistically significant. The lack of a significant difference between the positive PJ and other years implies that the strongest convective anomalies over the tropical WNP and apparent mid-latitude response found in the positive PJ years are not fully attributable to the BSISO amplitude, which is consistent with the aforementioned low correlation between the intraseasonal PJ index and BSISO amplitude subsampled from each BSISO phase group.

5. Conclusion

The intraseasonal PJ pattern is strongly linked with the BSISO, with the highest correlation during BSISO phase 8 when the associated active convection reaches the northern Philippines and Philippine Sea. The responses to the BSISO are apparent not only in the tropics but also in midlatitudes. In response to enhanced convective activities over the Philippine Sea during phases 5–7, surface low-pressure signals with cyclonic anomalies develop north of the Philippines, and a meridional pressure gradient becomes steep, which characterizes the positive PJ pattern. During BSISO phases 3–4, by contrast, the negative intraseasonal PJ pattern forms but with a weaker amplitude than the positive PJ pattern.

We further examine interannual modulations of this BSISO-intraseasonal PJ relationship. The intraseasonal PJ signals are more apparent in the BSISO events during the interannual positive PJ years. The wave train signals in SLP extending from north of the Philippines toward North America are observed only in the positive PJ years. This wave train pattern may be related to the PJ pattern derived by pentad data (Nitta 1987), intraseasonally filtered data (Kawamura et al. 1996), or in quasi-biweekly variability (Zhu et al. 2020), or a pressure pattern excited by tropical cyclones (e.g., Yamada and Kawamura 2007). Indeed, tropical cyclone occurrence is maximized in BSISO phase 7 (e.g., Yoshida et al. 2014). The contribution of tropical cyclones to the intraseasonal PJ pattern in BSISO phase 7 will be investigated in our ongoing study. In contrast, the intraseasonal PJ signals including the midlatitude response are weaker in the interannual negative PJ years than in the positive years, implying that the intraseasonal BSISO-PJ relationship is asymmetric between the interannual positive and negative PJ summers.

The interannual negative PJ pattern is known to appear more frequently during the post-El Niño summer (e.g., Xie et al. 2009, 2016), suggesting that the interannual mode is more dominant than the intraseasonal mode in the negative PJ pattern. It is also noteworthy that the differences between the positive PJ and other years in the mean amplitude and duration of the BSISO are small and not statistically significant, whereas the intraseasonal signals in OLR and SLP are generally stronger in the positive PJ years than in the other years. Further studies are needed to clarify the mechanism of the rapid intensification in convection and pressure anomalies in phases 5–7 during the positive PJ years, which cannot be explained solely by the BSISO amplitude.

The intraseasonal warm temperature anomalies found over eastern Eurasia extend eastward to the North Pacific during the convective phases of the BSISO, phases 5–6, which is important for the subseasonal forecast in East Asia. This midlatitude response in SAT also undergoes interannual modulations. Cold anomalies appear over eastern Eurasia in phase 5 in the positive PJ years, while temperature signals are weak and rather warm in the negative PJ years. These results suggest that summer subseasonal predictability in East Asia associated with the BSISO and the intraseasonal PJ pattern modulate interannually under the seasonal mean PJ pattern, which has important implications for extended forecasts.

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Fig. 4. Same as Fig. 3 (left) except for the BSISO events starting from phase 5 during (left) the negative PJ, (middle) positive PJ, and (right) the other years. Counter intervals are 0.3 K and thick contours represent ±0.9 K and stronger anomalies.
Fig. 5. Same as Fig. 3 (right) except for the BSISO events starting from phase 5 during (left) the negative PJ, (middle) positive PJ, and (right) the other years.
Supplements

Supplemental Fig. 1: Composite intraseasonal OLR anomalies for the BSISO events from phases 1 to 8. Only significant values at the 95% confidence level are shown. Purple (green) contours represent intraseasonal positive (negative) SAT anomalies with intervals of 0.15 K and thick contours indicate ±0.45 K and stronger anomalies. Dashed contours indicate ±0.075 K. The hatched area represents more than the 95% confidence level.

Supplemental Fig. 2: Composite intraseasonal SLP anomalies (hPa) for the BSISO events from phases 1 to 8. The dotted area indicates more than the 95% confidence level. Vectors indicate composite wind anomaly fields at 850 hPa (m s⁻¹), where either the zonal or meridional component is significant at the 95% level.

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