ABSTRACT

The influence of the Pacific decadal oscillation (PDO) on the relationship between El Niño and the northeast Asian summer monsoon (NEASM) is examined using observational datasets for the period of 1979–2007. When El Niño occurs during the boreal winter (December–February), the amount of rainfall over northeast Asia is usually above normal during the following summer (June–August). This relationship between El Niño and the NEASM is intensified when El Niño and the PDO are in phase during the previous winter. However, when El Niño and the PDO are out of phase, the relationship is weakened. The authors argue that the PDO can constructively or destructively interfere with the summer rainfall response over northeast Asia to El Niño.

They follow the hypothesis that the summer rainfall over northeast Asia could be separated into two components, that is, the tropics-related component and the extratropics-related component. Then they argue that the PDO could modulate the relationship between El Niño and the NEASM through changes in the extratropics-related rainfall, which is associated with the atmospheric circulation, such as the Eurasian pattern. The conditional composites show that when El Niño and the PDO are in phase, the Eurasian-like pattern acts to enhance the extratropics-related rainfall over northeast Asia, resulting in the strengthening of the NEASM. In contrast, the Eurasian-like pattern acts to reduce the extratropics-related rainfall when El Niño and the PDO are out of phase, resulting in the weakening of the NEASM.

1. Introduction

The summer monsoon over the Asian–Pacific region can be divided into three subsystems, that is, the East Asian summer monsoon, the western North Pacific summer monsoon, and the Indian summer monsoon (Chen et al. 1992; Krishnamurti 1985; Murakami and Matsumoto 1994; Tao and Chen 1987; Wang and LinHo 2002). Among them, the East Asian summer monsoon not only affects the climate of East Asia, but also exerts strong influence on climate in regions far from East Asia; therefore, it is an important component of the regional and global climate (Lau 1992; Lau and Weng 2002; Wang 2006). Furthermore, the East Asian summer monsoon is known to be one of the most complex monsoon systems because of the occurrence and persistence of various teleconnection patterns from both the tropics and the extratropics (Ogasawara and Kawamura 2008 and reference therein). Chang (2004) recently summarized the knowledge of the observed East Asian summer monsoon, including its seasonal characteristics, interannual variability, and interactions with various phenomena in the coupled atmosphere–ocean system (Lau and Nath 2006).

The East Asian summer monsoon consists of the northeast Asian summer monsoon (NEASM) and the Southeast Asian summer monsoon. The summer monsoon rainfall starts in June in the NEASM, whereas it starts about a month earlier in the Southeast Asian summer monsoon, including the South China Sea and surrounding landmasses (Wang 2004). Here we focus on the NEASM, which largely influences the summer climate condition over the region, including northeast China, Japan, and Korea (20°–50°N, 100°–180°E). The NEASM is represented by severe rainy season during the boreal summer [June–August (JJA)], which is associated with the rainfall variability along the so-called mei-yu (China), baiu (Japan), and changma (Korea) frontal bands. These major rainfall bands stretch over thousands of kilometers, and their variability is dominant on interannual time scales (Chang 2004). Such interannual variation in the NEASM is highly influenced...
by El Niño–Southern Oscillation (ENSO) via the Pacific–East Asian teleconnection (Huang and Wu 1989; Liu and Ding 1992; Shen and Lau 1995; Zhang et al. 1996; Chang et al. 2000; Lau and Nath 2000; Wang et al. 2000; Huang et al. 2004; Lau and Wang 2006). For instance, Huang and Wu (1989) argued that the summer rainfall anomaly in eastern China shows a very different distribution when comparing the ENSO developing year to the following year. On the other hand, it is well known that the meridional teleconnection patterns—such as the Pacific–Japan pattern—during summer have a predominant role in affecting the NEASM (Nitta 1989; Kawamura et al. 1996; Kosaka and Nakamura 2006; Ogasawara and Kawamura 2007; Kim et al. 2009). Previous studies also have shown that the relation between ENSO and the NEASM is variable on decadal time scales (Chang et al. 2000; Wu and Wang 2002; Kwon et al. 2005; Yim et al. 2008; Ding et al. 2010; Kim et al. 2009). All these studies have suggested that the NEASM has close connections with the state of sea surface temperature (SST) in the tropical Pacific (i.e., ENSO) and the tropical Indian Ocean on interannual-to-decadal time scales.

In addition to ENSO, SST anomalies (SSTAs) outside the tropics are also influential to the NEASM (Wang et al. 2000). While there is a wealth of studies on the influence of tropical SST on the NEASM, there are few studies to investigate connections between the NEASM and SSTAs outside the tropics. Here we examine the influence of North Pacific SSTAs on the NEASM, in particular the influence of the most dominant SST variability in the North Pacific, that is, the Pacific decadal oscillation (PDO; Mantua et al. 1997). Previous studies have argued that the PDO can modulate ENSO’s influence via atmospheric teleconnections around the Pacific basin (Barlow et al. 2001; Gershunov and Barnett 1998; Yeh and Kirtman 2004; Yu et al. 2007). Not surprisingly, Chan and Zhou (2005) showed that the phase of PDO is highly connected with amount of ENSO-related rainfall over south China. When ENSO is in phase with the PDO, the summer monsoon rainfall over south China tends to be below normal more often. In addition, Wang et al. (2008) argued that the contrast in ENSO’s influence between the two phases of the PDO should be taken into account in the ENSO-based prediction of wintertime climate over East Asia. However, there is little investigation on how the PDO is related to ENSO and the NEASM so far; therefore, it is worth examining the influence of the PDO on the relationship of ENSO and the NEASM.

The main purpose of the present study is to examine how the PDO modulates the relationship between El Niño and the NEASM in observations. Basically, the PDO mainly features Pacific decadal-to-interdecadal SST variability; however, it has a significant variability on interannual time scales as well (Schneider and Cornuelle 2005). Because of our data availability issue (1979–2007), we mainly focus on the influence of the PDO on the relation between El Niño and the NEASM on interannual time scales. In detail, we analyze the PDO modulation on the NEASM when El Niño is decaying from the boreal winter to the following summer. We examine how the PDO constructively or destructively interferes with the relationship between El Niño and the NEASM when El Niño decays.

The paper is organized as follows. Section 2 describes the data and methods in this study. In section 3, we compare the precipitation anomalies separating those associated with the tropics and midlatitude circulation changes. Then we discuss the roles of the midlatitude atmospheric condition on the modification of the relation and provide a summary in section 4.

2. Data and methodology

We use multiple observation datasets for the period January 1979–December 2007: monthly datasets of SST from the Met Office Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al. 2003), atmospheric fields from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996), and rainfall data from the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997).

El Niño is defined when the Niño-3.4 SST index during the boreal winter [December–February (DJF)] is above 0.5°C. The Niño-3.4 index during winter is defined as the time series of anomalous seasonal (i.e., DJF) mean SST over the region, 5°S–5°N, 170°–120°W. The PDO during winter is defined as the first empirical orthogonal function (EOF) in the North Pacific (20°–60°N, 110°E–110°W) using anomalous seasonal mean SST, and the PDO index is defined by the first principal component (PC) time series as in Mantua et al. (1997). For a comparison, we calculate a correlation coefficient between the PC time series and the PDO index by Mantua et al. (1997) (available online at http://jisao.washington.edu/pdo/PDO.latest). The correlation coefficient is 0.87, which is statistically significant at the 95% confidence level. A positive (negative) phase of the PDO corresponds to a case in which the PDO index is above (below) 0; therefore, a positive PDO phase corresponds to negative SST anomalies in the western and central North Pacific. Note that in this paper, 1980 DJF means December 1979–February 1980, and a linear trend is first removed from the SST dataset.

To represent the characteristics of the NEASM, we use the two northeast Asian summer monsoon indices
suggested by Lee et al. (2005, hereafter L05). One is the northeast Asian summer rainfall anomaly (NEASRA) and the other is the northeast Asian summer monsoon index (NEASMI). NEASRA is defined as the summer (JJA) rainfall anomaly averaged over 30°–50°N, 110°–145°E and NEASMI as the first PC time series of the EOF for summer rainfall anomalies over 20°–50°N, 100°E–180°W multiplied by the spatial-averaged value of the first eigenvector over the same region as NEASRA (i.e., 30°–50°N, 110°–145°E). The reader is invited to refer to L05 for a more detail explanation of these two indices, and we will further discuss these two indices in the section 3b.

3. Result

a. The PDO modulation

Nine El Niño events during winter occurred for the period 1980–2007. Among them, five El Niño events are accompanied with a positive phase of the PDO and four El Niño events are accompanied with a negative phase of the PDO (Table 1). Figure 1 displays the time series of the Niño-3.4 SST index and the PDO index during winter for the period 1980–2007. For convenience, all nine El Niño events during winter will be referred to as EN, five El Niño events with a positive phase of the PDO during winter will be referred to as EN+PDO, and four El Niño events with a negative phase of the PDO1 during winter will be referred to as EN-PDO.

Figure 2a shows the anomalous mean SST composite in the North Pacific in the case of EN. When El Niño events occurred, in general, the pattern of anomalous SST has anomalies of negative sign with an elliptical shape in the western and central North Pacific and anomalies of positive sign along the coast of North America, which is quite similar to the well-known structure of a positive phase of the PDO (Mantua et al. 1997). Figures 2b,c show the conditional composite of anomalous mean SST in the

1 The PDO index is close to 0 in 1992. The spatial pattern of North Pacific SST during winter in 1992 (not shown) has some differences with the PDO; however, anomalous warm SST dominates in the western and eastern North Pacific.
to be enhanced after El Niño (Zhang et al. 1996; Lau and Nath 2000; Wang et al. 2000; Chang et al. 2000; Wang and Lin Ho 2002). The spatial pattern of positive rainfall anomalies is characterized by a slight orientation to the southwest-to-northeast direction from eastern China to the western North Pacific. Such structure is associated with severe rainfall anomalies over northeast Asia along with the rainfall band such as the mei-yu, the baiu, and the changma, as we mentioned earlier.

Figures 3b,c are the same as Fig. 3a except for the case of EN+PDO and EN-PDO, respectively. It is striking that the anomalous summer rainfall in the case of EN-PDO (Fig. 3c) is quite different from that in the case of EN+PDO (Fig. 3b). When El Niño and the PDO are in phase during the previous winter (i.e., EN+PDO, Fig. 3b), the amount of anomalous rainfall over northeast Asia, including the western North Pacific around Japan, is large compared to the case when El Niño and the PDO are out of phase (Fig. 3c). The maximum anomalous rainfall exceeds 2 mm day\(^{-1}\) over the southeast of Japan in the case of EN+PDO. In the case of EN-PDO (Fig. 3c), in contrast, the conditional composite of anomalous rainfall shows a pattern of mixed negative and positive anomalies over northeast Asia. Therefore, the amount of anomalous rainfall in relation to the NEASM significantly differs between EN+PDO and EN-PDO. The NEASRA, which is averaged rainfall anomaly over the northeast Asian region (30\(^\circ\)–50\(^\circ\)N, 110\(^\circ\)–145\(^\circ\)E) is 0.34 mm day\(^{-1}\) in EN+PDO and –0.15 mm day\(^{-1}\) in EN-PDO, respectively. This indicates that the NEASM is stronger in the case of EN+PDO than that in the case of EN-PDO. Therefore, we argue that the PDO can constructively or destructively interfere with the summer rainfall response over northeast Asia to El Niño. To understand the details in the influence of the PDO, we provide the difference of the composite of anomalous rainfall over northeast Asia during summer between a positive and a negative phase of PDO (Fig. 4). Table 2 provides years when the PDO phase is positive and negative. In different phases of the PDO, there are large differences of anomalous rainfall over northeastern China, the southeast of Japan, and the western North Pacific where significant differences in the amount of anomalous rainfall are observed in the case of EN+PDO and EN-PDO (Figs. 3b,c). Again, this result supports the earlier-mentioned argument that there exists an interferential influence of the PDO on the relationship between El Niño and the NEASM.

b. Hypothesis

Before we explore how the PDO can modulate the relation of the NEASM to El Niño, we first introduce the argument suggested by L05. L05 hypothesized that the summer rainfall over northeast Asia could be separated into two components, that is, the tropics-related component and the extratropics-related component. L05 further showed that the tropics-related rainfall over northeast Asia is associated with ENSO, and the extratropics-related rainfall over northeast Asia is associated with the Eurasian (EU) pattern (Wallace and Gutzler 1981). Using the two northeast Asian summer monsoon indices (i.e., NEASRA and NEASMI), L05 showed that NEASMI represents the rainfall variability associated with the tropics-related component, whereas the difference between NEASRA and NEASMI [i.e., NEASRA – NEASMI] represents...
the rainfall variability associated with the extratropics-related component over northeast Asia.

Following L05, we also provide the first EOF of rainfall during summer from 1980 to 2007 over 20°–50°N, 100°E–180°W (Fig. 5a) and the time series of NEASMI in Fig. 5b (open circle). The first EOF rainfall explains 17.7% of the total variance. Note that NEASMI is defined to include a large region of the midlatitudes (i.e., 30°–50°N, 110°–145°E), compared to NEASRA. The first EOF indicates that the dominant structure of the NEASM rainfall is slightly oriented to the northeast and southwest from eastern China to the western North Pacific between 25° and 40°N (Fig. 5a), which is quite similar to that shown in L05 (their Fig. 1). The time series of NEASRA (closed circle) is embedded in Fig. 5b, and Fig. 5c shows the time series of NEASRA – NEASMI.

The time series of NEASMI (Fig. 5b) indicates the variability of summer rainfall associated with the tropics-related component over northeast Asia. Similar to the results in L05 (their Fig. 8), we also found that the time series of NEASMI is highly correlated with the tropical Pacific SST from the previous winter to the following summer during the entire analyzed period; however, it is not for the time series of NEASRA – NEASMI (not shown). The time series of NEASRA – NEASMI (Fig. 5c) indicates the variability of summer rainfall associated with the extratropics-related component over northeast Asia. As discussed in L05, we also calculate the correlation coefficient between the time series of NEASMR – NEASMI and the EU index (Wallace and Gutzler 1981) during summer for the period 1979–2007 and it is 0.57, which is statistically significant at the 95% confidence level. Note that the difference between normalized NEASRA and normalized NEASMI behaves similar to NEASRA – NEASMI. Further analysis indicates that NEASRA is more correlated with NEASRA – NEASMI than NEASMI. This is because NEASRA is defined to include a large region of the midlatitudes (i.e., 30°–50°N, 110°–145°E), compared to NEASMI. Therefore, NEASMI is more related to tropical circulation, whereas both NEASRA – NEASMI and NEASRA have a better correlation with extratropical circulation.

One may find that there are years when the sign for NEASMI (Fig. 5b) and NEASRA – NEASMI (Fig. 5c) is the same (i.e., 1984, 1987, 1991, 1993, 1994, 1997, 1998, 1999, 2001, 2003, 2004, 2006), and there are years when the sign for NEASMI and NEASRA – NEASMI is
different. This suggests that the tropics-related rainfall variability and the extratropics-related rainfall variability contribute differently to the summer rainfall variability over northeast Asia. Note that a simultaneous correlation coefficient between NEASMI and NEASRA – NEASMI for the entire analyzed period is close to zero. Furthermore, we provide the regressed summer rainfall anomaly against NEASMI and NEASRA – NEASMI in Figs. 6a,b, respectively. The spatial structure of rainfall variability associated with the tropics-related component (Fig. 6a) is quite different from that associated with the extratropics-related component (Fig. 6b). The regressed anomalous rainfall against the NEASMI (Fig. 6a) is mainly characterized by the rainband oriented to the northeast and southeast, which is quite similar to the spatial pattern of the first EOF rainfall over northeast Asia (Fig. 5a). On the other hand, the regressed anomalous rainfall against NEASRA – NEASMI (Fig. 6b) is characterized by three centers of regressed rainfall anomaly, located in South Korea, east Japan, and north China. By comparing with Figs. 6a,b, one may argue that the rainfall variability over South Korea and Japan could be influenced by both the tropics-related and the extratropics-related components. In summary, our results indicate that the hypothesis in L05 is still valid despite an extension of the analyzed period in this study. On the basis of this hypothesis in L05, a possible explanation for the PDO modulation on NEASM in relation to El Niño will be shown in the next subsection.

c. The PDO interference

In the previous subsection, we argued that the summer rainfall variability over northeast Asia is attributed to both the tropics-related component and the extratropics-related component. Our hypothesis is that the PDO may be associated with the rainfall variability in relation to the extratropics-related component. In other words, a different phase of the PDO may induce changes in the EU pattern, resulting in changes in the extratropics-related rainfall over northeast Asia. We argue that the PDO could modulate the summer rainfall over northeast Asia by influencing the extratropics-related rainfall through changes in the EU pattern.

To support this hypothesis, we first show the EU pattern based on the first EOF of anomalous 500-hpa geopotential height over the Eurasian continent (30°–67.5°N, 20°W–160°E) during summer (Tachibana et al. 2007) and its PC time series for the period 1979–2007 in Figs. 7a,b, respectively. The EU pattern explains about 24% of the total variance over the Eurasian continent. Note that we introduce the first EOF of anomalous 500-hPa geopotential height to represent the EU pattern in this study; however, the overall results change little when we use the EU index defined by Wallace and Gutzler (1981). The spatial structure of the EU pattern is characterized by a west–east wave train between 50° and 60°N from the western Eurasian continent to East Asia, which is quite similar to that suggested by previous studies (Barnston and Livezy 1987; Wallace and Gutzler 1981). However, the EU pattern defined by Wallace and Gutzler (1981) is the teleconnection pattern during winter; therefore, its spatial pattern is not consistent with that in Fig. 7a, although the overall structure is similar to some extent. This inconsistency may be due to the seasonality of teleconnections in the geopotential height field from winter to summer.

The PC time series of the EU pattern has little correlation with NEASMI, which represents the rainfall variability associated with the tropics-related component, for the period 1979–2007 (r = 0.02; here, r is a simultaneous correlation coefficient). In contrast, the PC

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TABLE 2. Classification of winter for 1980–2007 into PDO with a positive and negative phase.
The time series of the EU pattern are significantly correlated with the time series of NEASRA $^2$, which represents the rainfall variability associated with the extratropics-related component ($r \approx 0.63$). This result indicates that the EU pattern is associated with the rainfall in relation to the extratropics-related component over northeast Asia; furthermore, its variability is nearly independent of the rainfall variability in relation to the tropics-related component, which is consistent with the results in L05.

To check in more detail the relationship between the EU pattern and NEASRA $^2$, we provide the regressed anomalous 500-hPa geopotential height against NEASRA $^2$ during summer for the period 1979–2007 (Fig. 8). It is clear that the spatial pattern of regressed 500-hPa geopotential height (Fig. 8) is similar to the EU pattern as shown in Fig. 7a. A spatial pattern correlation between Figs. 7a and 8 is significantly high at 0.88. The regressed 500-hPa geopotential height against NEASRA $^2$ (Fig. 8) is characterized by anomalous low pressure over northeast Asia, and such an anomalous low pressure may contribute to enhance the rainfall associated with the extratropics-related component. To examine the interferential influence of the PDO on the relationship between El Niño and the NEASM, we display the conditional composite of anomalous 500-hPa geopotential height during summer in the case of EN+PDO and EN-PDO (Figs. 9a,b). In both cases, the composite of anomalous 500-hPa geopotential height is characterized by the EU-like pattern over the Eurasian continent (cf. box in Fig. 9). A pattern correlation coefficient of the conditional composite of anomalous 500-hPa height between the EN+PDO and EN-PDO is $-0.61$ over the Eurasian continent. Result in Figs. 9a,b suggests that a different phase of the PDO during the preceding winter may induce the EU-like pattern with a different sign in the extratropics during the following summer. In the case of EN+PDO (Fig. 9a), a west–east wave train is dominant between 50$^\circ$ and 60$^\circ$N and a center of anomalous low is located over northeastern China, where positive rainfall anomalies are observed (see Fig. 3). Such anomalous low pressure, which is associated with enhanced upward motion, may enhance the rainfall associated with the extratropics-related component over northeast Asia during summer. Therefore, a positive phase of the PDO constructively interferes with the relationship between El Niño and the NEASM. In the case of EN-PDO (Fig. 9b), in contrast, the EU-like pattern is characterized by an anomalous high over northeast Asia, and such anomalous high pressure may reduce the rainfall associated with the extratropics-related component over northeast Asia. Therefore, we may conclude that a negative phase of PDO destructively interferes with the relationship between El Niño and the NEASM. These results suggest that the phase of PDO can significantly modulate the El Niño–related summer rainfall variability over northeast Asia through changes in the atmospheric circulation, such as the EU-like pattern.
Lastly, we provide the composite of 500-hPa geopotential height in different phases of PDO to identify whether the PDO itself could induce changes in the EU-like atmospheric pattern. Figures 10a,b display the composite of geopotential height at 500 hPa during summer when the PDO is in a positive phase and a negative phase during the preceding winter, respectively, for the entire analyzed period. It is remarkable that the spatial patterns of 500-hPa geopotential height in different phases of the PDO reflect a mirror image, which is indicative of the influence of the PDO on the atmospheric variability in the extratropics. Note that the pattern correlation between the two composites over the Eurasian continent (Figs. 10a,b) is $r = 0.93$. The spatial pattern in the composite in a positive phase of the PDO (Fig. 10a), which is characterized by an elongated wave train from the west to the east between 50° and 60°N, is similar to that of the EU pattern (see Fig. 7). This result indicates that the different phases of the PDO can induce changes in the EU-like atmospheric pattern. We are arguing that there is a lagged relationship between the PDO during the preceding winter and the EU-like atmospheric pattern during the following summer. However, one may argue that the PDO directly influences the EU-like atmospheric pattern during summer. To examine this issue, we provide the regressed 500-hPa geopotential height during summer against the PDO index during the preceding winter (Fig. 11a) and during summer (Fig. 11b). Figure 11 indicates that the atmospheric circulation associated with the PDO during the preceding winter is more associated with the EU-like pattern than that during summer. We speculate that the PDO-related SST persistence from winter to summer is more effective at generating the EU-like atmospheric pattern. On the other hand, we may hypothesize that the lag and amplitude of atmospheric circulation response depends on the mixed layer depth (Sui et al. 2005). Because the North Pacific SST during winter is associated with a deep mixed layer depth through the surface cooling or the entrainment processes (Alexander and Deser 1995; Qu 2003), it plays a role as a sequestered heat reservoir that is able to modify the atmospheric circulation with a lagged time.

Furthermore, it is interesting to compare the composites in the different phases of the PDO (Figs. 10a,b) with that in the cases of EN+PDO and EN-PDO (Figs. 9a,b). Not surprisingly, the composite in a positive (negative) phase of the PDO shares some degree of similarity in terms of its spatial pattern with that in the case of EN+PDO (EN-PDO), but with a smaller magnitude. This suggests that the PDO during the preceding winter can modulate more effectively the EU-like atmospheric pattern.
pattern in the extratropics during the following summer when it accompanies El Niño.

4. Discussion and summary

In this study, we examined the influence of the PDO on the relationship between El Niño and the NEASM in observations. By using the Niño-3.4 SST index and the PDO index, we could categorize the two different types of El Niño that accompany a positive phase of the PDO (i.e., EN+PDO) and a negative phase of the PDO (i.e., EN-PDO) during winter. In general, the anomalous SST is characterized by anomalies of a negative sign with an elliptical shape from the western North Pacific to the central North Pacific, along with anomalies of an opposite sign in the east, south and north when El Niño events occurred during winter. It is shown that such a spatial pattern maintains in the North Pacific from winter to the following summer in the case of EN+PDO; however, it is not in the case of EN-PDO. When El Niño and the PDO are in phase during winter (i.e., EN+PDO), the NEASM is much stronger than that in the case of EN-PDO. These results suggest that the summer rainfall over northeast Asia could be modulated by the phase of the PDO during the previous winter.

To understand the PDO interference on the NEASM, we adopted the hypothesis suggested by L05 that the summer rainfall over northeast Asia could be separated into two components, that is, the tropics-related component and the extratropics-related component. L05 showed that the tropics-related rainfall over northeast Asia is associated with ENSO; on the other hand, the extratropics-related rainfall over northeast Asia is associated with the EU pattern. We hypothesized that the PDO may change the EU pattern, which is associated with changes in the extratropics-related rainfall variability over northeast Asia. Our analysis indicates that the phase of the PDO is able to induce changes in the EU pattern by itself. By directly comparing with the conditional composite of 500-hPa geopotential height in the cases of EN+PDO and EN-PDO, we found that a
different phase of the PDO during the preceding winter may induce the EU-like pattern with a different sign during the following summer. Such a difference in the EU-like pattern influences the rainfall associated with the extratropics-related component over northeast Asia. Therefore, we could conclude that the PDO constructively or destructively interferes with the relationship between El Niño and the NEASM through changes in the atmospheric circulation, such as the EU-like pattern.

To estimate quantitatively the fraction of the PDO influence to the total rainfall variance in the NEASM, we calculate the variances of NEASRA, NEASMI, and NEASRA – NEASMI (see Fig. 5), which represent the total rainfall variance, the tropics-related rainfall variance, and the extratropics-related rainfall variance, respectively, in the NEASM variability. It is found that the tropics-related (extratropics related) rainfall variance explains approximately 34% (66%) of the total rainfall variance.

Similarly, it is found that the PDO can also interfere with the summer rainfall response over northeast Asia to La Niña. In different phases of the PDO with La Niña (i.e., La Niña with a positive phase of PDO and La Niña with a negative phase of the PDO), there are large differences of anomalous rainfall over northeastern China, the southeast of Japan, and the western North Pacific (not shown). Interestingly, those are consistent with the region where significant differences in the amount of anomalous rainfall are observed in the cases of EN+PDO and EN-PDO.

We mainly focused on the influence of the PDO on the relationship between El Niño and the NEASM on interannual time scales. However, we could identify the effect of different phases of the PDO on decadal time scales, although the dataset is limited to the period of less than 30 years. According to previous studies, there is evidence of climate transition in the 1988/89 winter in the North Pacific basin climate (Hare and Mantua 2000; Hollowed et al. 2001; Yasunaka and Hanawa 2002; Overland et al. 2008). One may find such a shift in the PDO index seen in Fig. 1; that is, a positive phase of the PDO is dominant before 1989, while a negative phase of the PDO is dominant after 1989. Figure 12 displays the difference of rainfall composite of NEASM before and after 1989 when El Niño occurred during the preceding winter. There are some differences of rainfall distribution over northeast Asia during summer before and after 1989, indicating that a decadal-to-interdecadal PDO could influence the NEASM, in particular over northeastern China, and the southeast and northeast of Japan.

Despite an important role of the PDO on the relationship between ENSO and the NEASM, we could not exclude another important possibility. According to recent studies (Wakabayashi and Kawamura 2004; Ogawara and Kawamura 2008), there exist two summertime teleconnection patterns that originate from the midlatitudes—that is, the Europe–Japan pattern and the west Asian–Japan pattern—that significantly influence the East Asian summer monsoon variability. Among them, the Europe–Japan pattern (Wakabayashi and Kawamura 2004) shares some degree of similarity with the EU pattern, which needs to be verified by detail analysis. On the other hand, one may suggest a hypothesis that both the EU pattern and North Pacific SSTs are individually being affected by other atmospheric processes; therefore, the association between the PDO and EU might be because both are responding to the same internal atmospheric variability. For example, it has been shown that although the PDO modulates ENSO’s effects over North America, the relationship is not casual (Pierce 2002).

We also speculate that large differences in summer rainfall over northeast Asia are associated with different contributions of the tropics-related component in the cases of EN+PDO and EN-PDO. Figures 13a–c display the seasonal evolution of anomalous mean tropical Pacific SST from winter to the following summer in the case of EN+PDO. Figures 13d–f are the same as in Figs. 13a–c, except for the case of EN-PDO. As expected, the composite of seasonal SSTAs is different between EN+PDO and EN-PDO. In the case of EN+PDO, El Niño during winter (Fig. 13a) is characterized by large amplitude in the eastern equatorial Pacific. As the season progresses through the following spring and summer (Figs. 13b,c), El Niño gradually decays. However, anomalous warm SST is still observed in the far eastern equatorial Pacific during the following summer (Fig. 13c). In the case of EN-PDO, however, the maximum of anomalous mean SST is weak and its center is slightly shifted to the west during winter (Fig. 13d) compared to that in the case of EN+PDO. Furthermore, during the following summer

**Fig. 12.** The difference of rainfall composite of the NEASM before and after 1989 when EN occurred during the preceding winter. The contour interval is 0.5 mm day$^{-1}$ and the areas exceeding the 90% confidence level are shaded.
anomalous cool SST is observed in the far eastern central equatorial Pacific. There is no doubt that such different decaying processes in El Niño play an important role to induce changes in the rainfall associated with the tropics-related component over northeast Asia in the cases of EN+PDO and EN-PDO.

Lastly, we should acknowledge the issue of the statistical significance of the results in this study. Because of a limited period of data based on the CMAP, the sample size in the composite map is small in this study. As a result, the region where the statistics is significant is limited in the composite map. To ameliorate this concern, we attempt to analyze a much longer precipitation dataset covering the period 1958–2002 using the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) data (Uppala et al. 2005) and the period 1901–2002 using the land precipitation data of Climatic Research Unit, version 2.0 (CRU2.0; Hulme et al. 1998). Similarly, it is found that the NEASM is stronger in the case of EN+PDO than that in the case of EN-PDO (not shown), indicating that the PDO can constructively or destructively interfere with the summer rainfall response over northeast Asia to El Niño.

Furthermore, it is found that a phase of the PDO during winter could modify details of the summer precipitation pattern over northeast Asia, in particular over south China. However, our argument that the PDO is able to induce changes in the EU-like atmospheric pattern by itself is mainly based on a statistical analysis. To overcome this issue, therefore, an investigation using a long-term simulation of a coupled general circulation model and a much longer time series of data is necessary.

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