Influences of the Pacific Decadal Oscillation on the East Asian Summer Monsoon in non-ENSO years

Xiao Dong*

*Correspondence to: X. Dong, Institute of Atmospheric Physics, Chinese Academy of Sciences, 40# Huanshi Nanlu, Beijing 100029, P. R. China.
E-mail: dongxiao@mail.iap.ac.cn

Abstract

The impact of different phases of the Pacific Decadal Oscillation (PDO) on East Asia summer monsoon and related precipitation in non-ENSO (El Niño-Southern Oscillation) years is examined in this article. Associated with the large-scale sea surface temperature and circulation change, anomalous summer (JJA mean) precipitation in East China shows tripolar pattern, with increased (decreased) precipitation in the Yangtze-River Valley (North and South China) in positive PDO phase without ENSO. Besides, the western Pacific subtropical high exhibits expansion and westward shift in positive PDO phase along with significantly different sub-seasonal variation.

Keywords: Pacific Decadal Oscillation; East Asian Summer Monsoon; ENSO

1. Introduction

Since the late 1970s, with the notable decadal variation of global climate system, East Asian summer monsoon (EASM) has also experienced a decadal weakening, associated with the transition of summer precipitation pattern to a so-called ‘Southern Flood-Northern Drought’ regime (Wang, 2001; Zhou et al., 2009). In addition to the climatology of EASM, the relationship between El Niño-Southern Oscillation (ENSO) and EASM also experienced a decadal transition at the same time (Wang, 2002; Huang et al., 2010; Chowdary et al., 2012). Gao et al. (2006) showed the relation between ENSO and summer precipitation in East China weakened after the late 1970s. Wang et al. (2008) pointed out that the influence of ENSO on the western Pacific subtropical high (WPSH) strengthened since 1970s. Ye and Lu (2011) further examined the sub-seasonal variation of EASM and indicated that the ENSO-related rainfall anomalies in East China tend to be similar (reversed) between early and late summer before (after) the late 1970s, leading to the weakened relationship between ENSO and total summer rainfall in East China.

Pacific Decadal Oscillation (PDO), as an important signal at decadal time scales, shifted from its negative to positive phase after the late 1970s. Thus PDO is regarded as a leading factor that results in the decadal variation of both EASM and the relationship between ENSO and EASM. Yoon and Yeh (2010) found that when ENSO and PDO are in (out of) phase, the Eurasian-like pattern acts to enhance (reduce) the extratropics-related rainfall over northeast Asia, resulting in the strengthening (weakening) of the northeast Asian summer monsoon. Feng et al. (2014) showed that when ENSO is in (out of) phase with PDO, an anomalous tripolar (dipole) rainfall pattern exists in East China and WPSH experienced a one-time (two-time) northward shift. They further found that due to the phase transition of PDO, the life cycle of ENSO has changed, resulting in the different influence of ENSO on EASM in different PDO phases.

Note to say that although most previous researches focused on the influence of ENSO on EASM in different PDO phases (e.g. Xie et al., 2010), few studies separated the roles of ENSO and PDO played in influencing EASM. For example, it is still unclear whether PDO has a great impact on EASM in non-ENSO years. Based on available observation and reanalysis data, the influence of PDO on EASM in non-ENSO years will be examined in this study.

2. Data and methods

The monthly global land precipitation data used in this study, with the horizontal resolution 0.5° × 0.5°, are provided by the Climatic Research Unit at the University of East Anglia (Harris et al., 2014). The monthly sea level pressure (SLP) data are provided by the Met Office Hadley Centre (HadSLP2). The horizontal resolution of HadSLP2 is 5° × 5° (Allan and Ansell, 2006). The monthly sea surface temperature (SST) data (Extended Reconstructed Sea Surface Temperature, ERSST v3b), are provided by the National Oceanic and Atmospheric Administration (Smith et al., 2008). The monthly PDO index, which is defined as the leading EOF of mean SST anomalies for the Pacific Ocean to the north of 20°N, is provided by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO). Niño3.4 index is the average sea surface temperature anomaly in the region bounded by 5°N–5°S, from 170 to 120°W. In addition, the ERA-40 reanalysis data (2.5° × 2.5°) from the European Centre for Medium-Range Weather Forecasts are also used here to...
examine the general circulation associated with EASM (Uppala et al., 2005).

The non-ENSO years used for composite analysis are selected as following steps. First, as in Feng et al. (2014), an El Niño (La Niña) year is selected when the boreal winter (DJF) mean normalized Niño3.4 index is greater (lower) than 0.5. Based on this definition, 16 El Niño (18 La Niña) events are picked out (Table 1). Due to the fact that EASM suffers more influence in ENSO decaying years through the Indian Ocean capacitor effect (e.g. Xie et al., 2009; Huang et al., 2010; Chowdary et al., 2011), we discard all ENSO decaying summers. Then there are total 22 non-ENSO years left, among which 12 (8) years are in the positive (negative) PDO phase during 1958–2012 (Table 2). There are still two years (1959 and 1960) that are excluded in our analysis because the absolute values of the PDO index in these 2 years are rather small (less than 0.1) that they can be regarded as ‘normal’ PDO years (Figure 1). In the following section, the composite differences between positive and negative PDO phases for the selected non-ENSO years are mainly discussed. Note that most positive (negative) PDO years are after (before) 1980, which may be related to the decadal shift of the PDO phase. Then to avoid biases of the composites results from the long-term trend, the SST and SLP data are first detrended before composite analysis.

3. Results

3.1. Large-scale circulation

Figure 2 shows the pattern of the difference of large-scale SST and SLP between positive and negative PDO phases in non-ENSO years. It can be clearly seen that in positive PDO years, the central and eastern tropical Pacific and the northeast and southeast subtropical Pacific experience notable warming, accompanied by cooling in the central and western part in both North and South Pacific in mid-latitude. The symmetry feature of SST along the equator reminds us that the generation mechanism of PDO may be originated from tropical region (Newman et al., 2003; Shakun and Shaman, 2009). Associated with the positive PDO phase, the South Indian Ocean (30–60°S) and the warm pool region mainly experience warming. In addition, in the mid-latitude North and South Atlantic Ocean, there are notable warming regions associated with positive PDO phase. The intimate relationship between the Pacific and other Oceans in different PDO phases may be resulted from both atmospheric teleconnections and oceanic processes that connecting them (Liu and Alexander, 2007).

In non-ENSO years, SLP also exhibits notable large-scale pattern associated with difference PDO phases. The negative anomaly mainly appears in the central and eastern parts of the Pacific in both low and middle latitudes, associated with positive SST anomaly there in positive PDO phase. Besides, the negative anomaly also appears south to Australia and in most part of North America and western part of the Atlantic. Meanwhile, significant positive anomaly appears above the central Eurasia, the Indian Ocean, Greenland region and South Pacific at about 60°S. Resulted from the fact that the Asian summer monsoon is mainly originated from the land–sea thermal contrast in boreal summer, the positive SLP anomaly above the Asian continent in positive PDO phase is in favor of weakening of the Asian summer monsoon (anomalous northerly in East China in Figure 2(c)), consistent with the fact that EASM experienced decadal weakening along with the phase transition of PDO from negative to positive phase in the late 1970s.

Associated with the large-scale SST and SLP changes, notable shifts occur in the low-level wind field (Figure 2(c)). Two cyclonic anomalies are located in the North Pacific and North Atlantic, respectively, which are related to the reduced SLP there (Figure 2(b)). Besides, anomalous westerly exists in eastern Indian Ocean and tropical Pacific, which may be due to the anomalous pressure gradient pointing to the east resulted from the spatial pattern change that SLP increase in the west and decrease in the east (Figure 2(b)). In addition, a cyclonic (anti-cyclonic)

---

**Table 1. El Niño and La Niña decaying years.**

| ENSO years | Years |
|------------|-------|
| El Niño    | 1958, 1966, 1969, 1973, 1978, 1981, 1987, 1988, 1991, 1992, 1995, 1998, 2003, 2005, 2007 and 2010 |
| La Niña    | 1963, 1964, 1965, 1968, 1971, 1974, 1976, 1985, 1989, 1996, 1999, 2000, 2001, 2006, 2008, 2009, 2011 and 2012 |

**Table 2. Non-ENSO years based on different PDO phases.**

| Non-ENSO years | PDO+(12) | 1957, 1977, 1979, 1980, 1981, 1982, 1984, 1986, 1993, 1997, 2002 and 2004 |
|---------------|---------|-----------------------------|
| PDO-(8)       | 1961, 1962, 1967, 1970, 1972, 1975, 1990, 1994 |

---

**Figure 1.** Normalized time series of the Pacific decadal oscillation (PDO) index (green line) and Niño3.4 index (red line). Black (Blue) solid circles denote the selected positive (negative) PDO index of the non-ENSO years. Red hollow circles denote the corresponding Niño3.4 index of the selected non-ENSO years. Grey circles denote the PDO index of 1959 and 1960 that are excluded in the analysis (See context for detailed information).
anomaly is in the subtropical (middle to high latitude) South Pacific. The circulation anomaly is intimately associated with the spatial pattern of SLP change.

3.2. Influence on Asian monsoon

Figure 3(a) shows the spatial pattern of the summer (JJA mean) precipitation difference between positive and negative PDO phases in non-ENSO years. The precipitation change in East China shows a tripolar pattern in which precipitation increase (decrease) in the Yangtze-River valley (North and South China). Besides, in positive PDO years, there are negative precipitation anomaly in the Indo-China Peninsula and northern part of Mongolia. Our results are consistent with previous research on East Asia, in which results

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Composites of the difference of (a) Sea surface temperature (SST, °C), (b) Sea level pressure (SLP, hPa) and (c) 850-hPa wind field (m/s) in boreal summer between positive and negative PDO phases in non-ENSO years. Cross denotes values that exceeds 10% significance level based on the two-sided Student's t-test.
showed that after the late 1970s summer precipitation in East China exhibits tripole nodes pattern with positive precipitation anomaly in the Yangtze River Valley and negative anomaly in North and South China, associated with transition of PDO from negative to positive phase (Ma, 2007; Zhou et al., 2009). This indicates that even though the impacts of ENSO on summer precipitation in East China in different PDO phases are removed, phase change of PDO alone can result in the tripole nodes rainfall pattern in East China. Besides, Feng et al. (2014) showed that in the El Niño decaying summer in positive PDO phase, anomalous rainfall pattern in East China also exhibits tripole nodes, which is similar to our Figure 3(a) (their Figure 5). Thus the contribution to the rainfall pattern change in different PDO phases can be resulted from both change of PDO phase alone and change of El Niño influence in different PDO phases as investigated by Feng et al. (2014).

Due to the intimate association between summer precipitation in East Asia and WPSH, Figure 4(a) shows the position of WPSH in different PDO phases in non-ENSO years. 5870 gpm contour line at 500 hPa is regarded as the position of WPSH. It can be seen that the range of WPSH is notably larger in positive PDO phase than that in negative phase, accompanied by more westward extension of the most western point of WPSH in positive PDO phase. This may be attributed to the systematically positive anomaly of the geopotential height at 500 hPa at low latitudes, which may be related to the tropical warming in positive PDO phase (Figure 2). Besides, Yu et al. (2015) showed that the eastern tropical Pacific warming can cause a strengthened WPSH through affecting the zonal circulation. The westward extension of WPSH in positive PDO phase may be the cause of increased precipitation along the Yangtze-River. The topic on the relationship between the westward extensions of WPSH and rainfall change in East China has been extensively investigated (See Zhou et al. (2009) for a review).

3.3. Sub-seasonal variation

EASM also bears notable sub-seasonal variation (Ye and Lu, 2011; Feng et al., 2014). Thus the different sub-seasonal march of EASM precipitation and associated WPSH between positive and negative PDO phases in non-ENSO years are further examined (Figure 3(b)–(d)). In June, there are anomalous positive rainfall regions in North and Northeast China. Meanwhile the anomalous rainfall in East China is less significant. In July, there is significant positive rainfall anomaly along the Yangtze River near 30°N.
Influences of the Pacific Decadal Oscillation on the East Asian Summer Monsoon

Figure 4. (a) Composites of the JJA mean position of WPSH, which is denoted by the 5870 gpm contour line at 500-hPa, in boreal summer in positive (solid line) and negative (dashed line) PDO phases in non-ENSO years. (b-d) Composites of June, July and August, respectively, mean position of WPSH, which is denoted by the 5870 gpm contour line at 500-hPa, in boreal summer in positive (solid line) and negative (dashed line) PDO phases in non-ENSO years.

and the negative rainfall anomaly is mainly in North and Northeast China and Mongolia. The contribution to the JJA mean precipitation pattern change is dominantly resulted from that in July. In August, the rainfall anomaly is similar to that in July with less significance. Besides, the negative precipitation anomaly in Northeast China in July is replaced by positive rainfall anomaly in August.

WPSH also experiences notable northward shifts with the seasonal march of the monsoon circulation and rain-belt (Figure 4(b)–(d)). Along with the northward shifts, WPSH also exhibits eastward retreat in both positive and negative PDO phases. In positive PDO phase, the coverage of WPSH is larger and the WPSH extends westward in June and July, favoring the transport of moisture into East China, resulting in the positive precipitation anomaly. However, it is surprising that in August, the eastward retreat of WPSH is more notable in positive than that in negative PDO phase. The reason why the variation of WPSH in August in different PDO phases is not same as in June and July may be attributed to the fact that in August the WPSH is located more northward than in June and July. While in June and July the low latitude warming in positive PDO phase prefers the expansion of WPSH, in August the mid-latitude cooling in North Pacific during positive PDO phase may induce the WPSH to retreat more notably than in June and July. Further studies are still needed to investigate the mechanisms of air–sea coupling in mid-latitudes in low frequency variability (e.g. Barsugli and Battisti, 1998).

4. Summary

In this study, the impact of different phases of PDO on EASM and related summer precipitation in non-ENSO years is explored. Results show that in positive PDO years without ENSO, the central and eastern tropical Pacific experience notable warming, accompanied by cooling in the central and western part in both North and South Pacific in mid-latitude. Besides, the South Indian Ocean and middle to high latitude of North Atlantic also experience warming. Meanwhile SLP decrease in central and eastern parts of the whole Pacific and increase in the central Eurasia and the Indian Ocean result in eastward wind anomaly at low level in warm pool region and tropical Pacific. Besides, the SLP change also favors the weakening of EASM. Along with the large-scale SST and circulation change, anomalous summer (JJA mean) precipitation in East China shows tripolar pattern, with increased (decreased) precipitation in the Yangtze River Valley and negative anomaly in North and South China, associated with transition of PDO from negative to positive phase (Ma, 2007; Zhou et al., 2009). Combining our results with that from previous studies (e.g. Feng et al., 2014), it can be concluded that the contribution to the rainfall pattern change in different PDO phases
can be resulted from both change of PDO phase alone and change of El Niño influence in different PDO phases. Besides, while the WPSH exhibits expansion and westward shift in positive PDO phase in June and July, it retreats more significant in August, exhibiting notable sub-seasonal variation in different PDO phases.

Acknowledgements
The author thanks two anonymous reviewers and Editor A. J. Miller for their constructive comments. This study was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA05110201) and Natural Science Foundation of China (Grant No. 41475052).

References
Allan R, Ansell T. 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850-2004. Journal of Climate 19: 5816–5842.

Barsugli JJ, Battisti DS. 1998. The basis effects of atmosphere-ocean thermal coupling on midlatitude variability. Journal of the Atmospheric Sciences 55(4): 477–493.

Chowdary JS, Xie SP, Luo JJ, Hafner J, Behera S, Masumoto Y, Yamagata T. 2011. Predictability of Northwest Pacific climate during summer and the role of the tropical Indian Ocean. Climate Dynamics 36: 607–621.

Chowdary JS, Xie S, Tokinaga H, Okumura YM, Kubota H, Johnson N, Zheng X-T. 2012. Interdecadal variations in ENSO teleconnection to the Indo-Western Pacific for 1870-2007. Journal of Climate 25: 1722–1744.

Feng J, Wang L, Chen W. 2014. How does the east Asian summer monsoon behave in the decaying phase of El Niño during different PDO phases? Journal of Climate 27: 2682–2698.

Gao H, Wang Y, He J. 2006. Weakening significance of ENSO as a predictor of summer precipitation in China. Geophysical Research Letters 33: L09807.

Harris I, Jones PD, Osborn TJ, Lister DH. 2014. Updated high-resolution grids of monthly climatic observations–the CRU ts3.10 dataset. International Journal of Climatology 34: 623–642.

Huang G, Hu K, Xie SP. 2010. Strengthening of tropical Indian Ocean teleconnection to the northwest Pacific since the mid-1970s: an atmospheric GCM study. Journal of Climate 23: 5294–5304.

Liu Z, Alexander M. 2007. Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. Reviews of Geophysics 45: 623–626.

Ma Z. 2007. The interdecadal trend and shift of dry/wet over the central part of North China and their relationship to the Pacific Decadal Oscillation (PDO). Chinese Science Bulletin 52(15): 2130–2139.

Newman M, Compo GP, Alexander MA. 2003. ENSO-forced variability of the Pacific Decadal Oscillation. Journal of Climate 16(23): 3853–3857.

Shakun JD, Shaman J. 2009. Tropical origins of North and South Pacific decadal variability. Geophysical Research Letters 36: L19711, doi: 10.1029/2009GL040313.

Smith TM, Reynolds RW, Peterson TC, Lawrimore J. 2008. Improvements NOAA’s historical merged land–ocean temp analysis (1880–2006). Journal of Climate 21: 2283–2296.

Uppala SM, Källberg PW, Simmons AJ, Andrae U, Bechtold VDC, Fiorino M, Gibson JK, Haseler J, Hernandez A, Kelly GA, Li X, Onogi K, Sarrinen S, Sokka N, Allan RP, Andersson E, Arpe K, Balmaseda MA, Beljaars ACM, Van De Berg L, Bidlot J, Bormann N, Caires S, Chevallier F, Dethof A, Dragosavac M, Fisher M, Fujitsu M, Hagemann S, Hólm E, Hoskins BJ, Isaksen L, Janssen PAEM, Jenne R, McNally AP, Mahfouf J-F, Morcrette J-J, Rayner NA, Saunders RW, Simon P, Sterl A, Trenberth KE, Untch A, Vasiljevic D, Viterbo P, Woollen J. 2005. The era-40 re-analysis. Quarterly Journal of the Royal Meteorological Society 131(612): 2961–3012.

Wang HJ. 2001. The weakening of the Asian monsoon circulation after the end of 1970s. Advances in Atmospheric Sciences 18: 376–386.

Wang HJ. 2002. The instability of the East Asian summer monsoon-ENSO relations. Advances in Atmospheric Sciences 19: 1–11.

Wang B, Yang J, Zhou T, Wang B. 2008. Interdecadal changes in the major modes of Asian-Australian monsoon variability: strengthening relationship with ENSO since the late 1970s. Journal of Climate 21: 1771–1789.

Xie SP, Hu K, Hafner J, Tokinaga H, Du Y, Huang G, Sampe T. 2009. Indian Ocean capacitor effect on Indo-western Pacific climate during the summer following El Niño. Journal of Climate 22: 730–747.

Xie SP, Du Y, Huang G, Zheng X-T, Tokinaga H, Hu K, Liu Q. 2010. Interdecadal change of the 1970s in El Niño influences on Indo-western Pacific and East Asian climate. Journal of Climate 23: 3352–3368.

Ye H, Lu R. 2011. Subseasonal variation in ENSO-related East Asian rainfall anomalies during summer and its role in weakening the relationship between the ENSO and summer rainfall in eastern China since the late 1970s. Journal of Climate 24: 2271–2284.

Yoon J, Yeh SW. 2010. Influence of the Pacific decadal oscillation on the relationship between El Niño and the northeast Asian summer monsoon. Journal of Climate 23: 4525–4537.

Yu L, Furevik T, Otterå OH, Gao Y. 2015. Modulation of the Pacific Decadal Oscillation. Journal of Climate 28(11): 475–494.

Zhou T, Gong D, Li J, Li B. 2009. Detecting and understanding the multi-decadal variability of the East Asian summer monsoon—Recent progress and state of affairs. Meteorologische Zeitschrift 18: 455–467.