ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **17**: 531–537 (2016)
Published online 22 August 2016 in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl.688

Royal Meteorological Society

The North Pacific Gyre Oscillation and East Asian summer precipitation

Xiaoyan Ye,[1] Wei Zhang[2,3] and Ming Luo[4]*

[1] *National Engineering Research Center of Geospatial Information Technology, Fuzhou University, China*
[2] *NOAA/Geophysical Fluid Dynamics Laboratory and Atmospheric Oceanic Sciences Program, Princeton University, NJ, USA*
[3] *Key Laboratory of Meteorological Disaster, Ministry of Education, Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, and Earth System Modeling Center, Nanjing International Academy of Meteorological Sciences, Nanjing University of Information Science and Technology, China*
[4] *Institute of Energy, Environment and Sustainability, The Chinese University of Hong Kong, Sha Tin, NT, Hong Kong*

Correspondence to: M. Luo, Institute of Energy, Environment and Sustainability, The Chinese University of Hong Kong, Sha Tin, NT, Hong Kong. E-mail: luoming@cuhk.edu.hk

Received: 6 January 2016
Revised: 18 July 2016
Accepted: 20 July 2016

Abstract

This study examines the links between the North Pacific Gyre Oscillation (NPGO) and the East Asia (EA) summer precipitation (EASP) at a decadal scale. Maximum covariance analysis reveals that NPGO is the third mode regulating the decadal variation of EASP. 'Global warming' and Pacific Decadal Oscillation are the first two leading modes. Associated with NPGO, EASP exhibits a north-to-south '+ − +' tripole pattern. The related atmospheric circulations are also examined. Results demonstrate that the linkage between NPGO and EA involves two processes, namely, extratropical and tropical processes. In the extratropical process, NPGO features an eastward propagating Rossby wave over the extratropical regions; this wave intensifies and displaces the EA jet stream northward. In the tropical process, NPGO is associated with a meridional circulation over the northeastern Pacific and an anomalous Walker circulation over the tropical oceans. The anomalous Walker circulation exhibits a downward branch over the western tropical Pacific and features low-level northerly wind over EA and western North Pacific region. The two processes strengthen the EA summer monsoon circulation and enhance the moisture transportation from oceans to northern EA; thus, the precipitation in the northern EA region increases and the precipitation in the central region decreases.

Keywords: decadal variability; East Asia summer precipitation; North Pacific Gyre Oscillation; sea surface temperature; Silk-Road teleconnection; Walker circulation

1. Introduction

The variability of precipitation over East Asia is considerably modulated by the variation of sea surface temperature (SST). Previous work suggested that El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are specifically the dominant causal factors at the interannual scale (Chang *et al.*, 2000; Wang *et al.*, 2000; Ding and Chan, 2005; Luo *et al.*, 2015, 2016). For instance, an El Niño-like SST pattern in June 2015 intensified the western Pacific subtropical high and shifted it southwestward, thus increasing the occurrence of heavy precipitation in eastern China (Wang and Gu, 2016). Besides, the Indian Ocean basin warming is also an important recognized driver of the East Asian summer rainfall (Xie *et al.*, 2009). In addition, the decadal variation of East Asia summer precipitation (EASP) has been documented in some studies (Kwon *et al.*, 2007; Ding *et al.*, 2008; Zhou *et al.*, 2009). Global warming is suggested as a dominant factor that modulates the long-term change in EASP (Yu *et al.*, 2004; Kimoto, 2005; Li *et al.*, 2010). Moreover, the Pacific Decadal Oscillation (PDO) is the first leading mode of sea surface height anomaly (SSHA) and SST anomaly (SSTA) in the North Pacific; PDO is another fairly important mode with respect to East Asian climate systems (Wu and Wang, 2002; Ding and Chan, 2005; Ding *et al.*, 2008; Pei *et al.*, 2015).

The North Pacific Gyre Oscillation (NPGO) has been identified as the second pattern of the North Pacific climate variability (Di Lorenzo *et al.*, 2008). Previous studies demonstrated that the atmospheric forcing pattern of NPGO is the North Pacific Oscillation (NPO) (Chhak *et al.*, 2009). NPGO is suggested to be influential on the East Asian climate on the interannual scale (Wang *et al.*, 2007, 2011; Choi *et al.*, 2011). Its relationship with East Asian climate may exhibit decadal changes (Wang *et al.*, 2007; Zhou and Xia, 2012; Pak *et al.*, 2014). The North Pacific SSTA footprint of the NPGO is essentially identical to the Victoria Mode (Bond *et al.*, 2003), which is the second leading pattern of variability of North Pacific SSTA. NPGO shows a more decadal viability than the Victoria Mode does (Yi *et al.*, 2015). NPGO is closely related to ENSO, specifically the central Pacific El Niño (Di Lorenzo *et al.*, 2010).

Some studies have shown that NPGO significantly influences East Asian climate. For example, Zhang *et al.* (2013) found that NPGO is significantly associated with the occurrences of tropical cyclones in East Asia and western North Pacific. The relationship between NPGO and winter precipitation in East Asia has also been investigated (Zhang *et al.*, 2011; He and Wang, 2013). Nonetheless, the association between NPGO and East Asian summer precipitation has yet to be documented. NPGO may play a pivotal role in shaping the climate system during global warming (Di Lorenzo *et al.*, 2008; Lienert and Doblas-Reyes, 2013). This oscillation is also essential for the global climate system; hence, the mechanism and the extent to which NPGO influences East Asian summer precipitation should be elucidated.

The remaining parts of this article are organized as follows. Section 2 introduces the data and methods. Section 3 presents the analysis results. Section 4 discusses the interpretation of the results. Section 5 presents conclusion, with a summary and some remarks.

2. Data and methodology

The precipitation dataset used in this study is obtained from Global Precipitation Climatology Center (GPCC); this dataset covers 1901–2008 in the East Asian region (105°–145°E, 20°–45°N). The Full Data Product (V6) of GPCC in 1901–2008 is used, with a spatial resolution of $1° \times 1°$ latitude by longitude (Schneider *et al.*, 2011). SSTA data are derived from the Kaplan SSTA dataset with a spatial resolution of $5° \times 5°$ (Kaplan *et al.*, 1998). The atmospheric reanalysis dataset is obtained from the National Centers for Environmental Prediction (NCEP) 20th Century Reanalysis V2 (Compo *et al.*, 2011). SSH data are acquired from Simple Ocean Data Assimilation reanalysis (Carton and Giese, 2008), and the NPGO index is defined as the temporal coefficient of the second Empirical Orthogonal Function (EOF) of the detrended SSHA in the northeast Pacific (NEP) region (179.75°E–110.25°W, 24.75°E–62.25°N) (Di Lorenzo *et al.*, 2008; Yi *et al.*, 2015).

Five-year Butterworth low-pass filtering (Butterworth, 1930) is applied to extract low-frequency signals from the time series of climate indices and the related atmospheric variables. Anomalies are determined by removing the climatological average from 1951 to 1980. Maximum covariance analysis (MCA) is conducted to identify the coupling relationship between filtered GPCC precipitation and Kaplan SST anomalies (Von Storch, 1999; Von Storch and Zwiers, 2001). Pearson correlation and regression analysis are employed to derive the association among variables (Von Storch and Zwiers, 2001).

3. Analysis results

This study initially uses MCA to identify the coupling relationship between precipitation anomalies in East Asia and SSTA. Among the four dominant coupling modes identified by MCA, the first two leading modes correspond to global warming and PDO, respectively (Figure S1, Supporting information). The influences of global warming and PDO on East Asian summer precipitation have been investigated (Wu and Wang, 2002; Yu *et al.*, 2004; Pei *et al.*, 2015). In our study, the third mode accounting for 10% of the total variance is mainly examined.

Figure 1 illustrates the spatial and temporal coefficients of the third coupling MCA mode. The precipitation in East Asia exhibits a tripole pattern: positive precipitation anomalies appear in northern East Asian regions, such as North and Northeast China, northern Korea Peninsula, and northwestern coastal regions of Japan, and southern East Asian regions, such as South China. By contrast, negative precipitation anomalies form in the central East Asian region, mainly in middle and lower Yangtze River Basin (YRB) and southeastern coastal region of Japan (Figure 1(b)). This pattern resembles Figure 1(c) of Zhang (2015) that shows the differences in precipitation between 2001–2008 and 1990–2000, suggesting that NPGO may play important role in the decadal changes of the EA summer precipitation since the 1990s. Meanwhile, SSTA exhibits a northeast–southwest-oriented tripole pattern, including a dipole correlation pattern in the North Pacific poleward of 20°N and a subtropical pole of positive correlations located in the central–eastern North Pacific (Figure 1(c)). This pattern is close to the SSTA regression pattern associated with the NPGO index and Victoria Mode (Bond *et al.*, 2003).

The temporal coefficients of precipitation and SSTA show a strong decadal variation, and the two time-series phenomena yield a high correlation coefficient of 0.79 ($p < 0.001$). The correlation coefficients between the NPGO index and two temporal coefficients of precipitation and SSTA are >0.80 ($p < 0.001$). These results suggest that this coupling mode is mainly modulated by NPGO, and NPGO plays an important role in the decadal variability of summer precipitation in East Asia. It is noted that employing MCA may imply symmetry of the anomalies. However, the relationship between NPGO and EA summer precipitation is significant. The mechanisms and atmospheric processes underlying this relationship are investigated in the following parts.

Figure 2 depicts the atmospheric conditions associated with the precipitation pattern by illustrating the regression charts of the surface air temperature (T2m), sea level pressure (SLP), 500-mb geopotential height (Z500) and vertical velocity (ω500) on the normalized NPGO index. Cooling anomalies cover the most parts of northern East Asia, and the maximum anomaly forms in North China at approximately 110°E and 45°N (Figure 2(a)). SLP exhibits a northern–central–southern tripole pattern (Figure 2(b)), which corresponds to the spatial pattern of precipitation (Figure 1(b)). This tripole pattern can also be observed in ω500 (Figure 2(c)). In

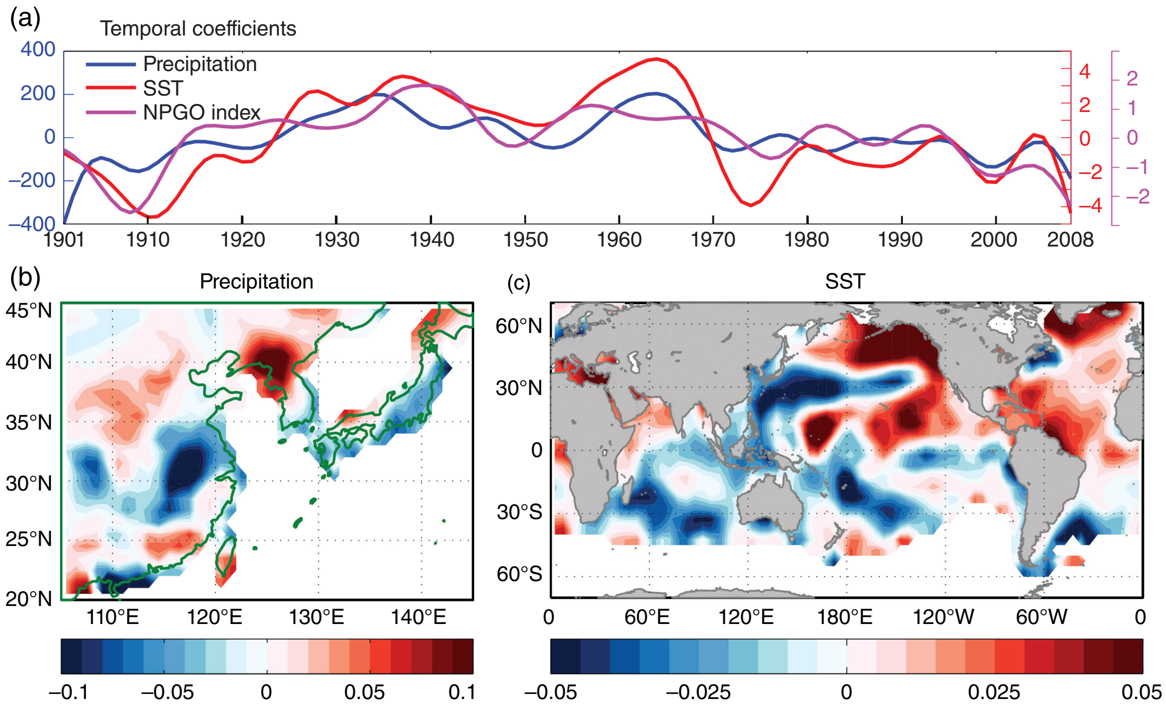

Figure 1. Third mode of MCA on 5-year Butterworth low-pass filtered summer (May–September) precipitation in East Asia (105°–145°E, 20°–45°N) and filtered global SST. (a) Temporal coefficients of precipitation (blue) and SSTA (red), and normalized NPGO index (purple); (b) spatial coefficients of precipitation anomaly; and (c) spatial coefficients of SSTA.

this pattern, descending motions appear in northern and southern East Asia, whereas ascending motions form over both the central eastern China and the northern Korean Peninsula. These ascending motions are consistent with the low-level convergence along the Meiyu band (Figure 4(c)), a favorable large-scale configuration for enhanced precipitation over central eastern China (Huang *et al.*, 2012). In contrast, as shown in Figure 2(d), water vapor anomalies are divergent (convergent) over the central eastern China (the northern Korean Peninsula). In this sense, the reduced (enhanced) precipitation over the central East China (the northern Korean Peninsula) (Figure 1(b)) is mainly determined by the convergence of water vapor (Figure 2(d)). The distribution of water vapor convergence is likely to be related to the anomalous low-level divergence center over the South China (Figure 4(d)), which is linked to an anomalous Walker circulation induced by NPGO.

These findings explain the underlying factors influencing the spatial pattern of precipitation. However, the physical mechanisms implicated in the linkage between the East Asian summer precipitation and NPGO should be investigated. These mechanisms are discussed in the following section.

4. Possible mechanisms

Foregoing analysis reveals that NPGO is significantly associated with the decadal variation of the summer precipitation in East Asia. In this section, geopotential height, winds, velocity potential, and divergent winds are evaluated to elucidate the processes underlying the association. Possible mechanisms include extratropical and tropical processes via an eastward propagating wave-train and modification of the Walker circulation, respectively.

4.1. Extratropical process

Figure 3(a) illustrates the spatial regression of geopotential height at 250-mb level on the normalized NPGO index. At 250-mb level, the geopotential height exhibits a dipole pattern in NEP, with a high center appearing in the northern region and a low center in the southern region. This pattern corresponds to the second EOF of SSHA in the NEP (Di Lorenzo *et al.*, 2008; Yi *et al.*, 2015). This geopotential height pattern also features a zonal wave-train pattern in the high-latitude region. Figure 3(b) shows the wave activity flux on the NPGO index at 250-mb level (Plumb, 1985). It is observed that the wave-train corresponds to the eastward propagating Rossby waves (Shaman and Tziperman, 2007). This wave-train manifests over the NEP region, and then passes through North America, Atlantic, and the Eurasian continents and generates intensified 250-mb geopotential height over the northern East Asia (Figure 3(a)).

This given event is an extratropical process that connects NEP and East Asia mainly via the modification of East Asian jet stream (EAJS). Furthermore, the anomalous 250-mb height is accompanied by a change in EAJS. As shown in Figure 3(a), anomalous 250-mb westerlies appear in the central and northern side of EAJS; conversely, easterly wind anomalies

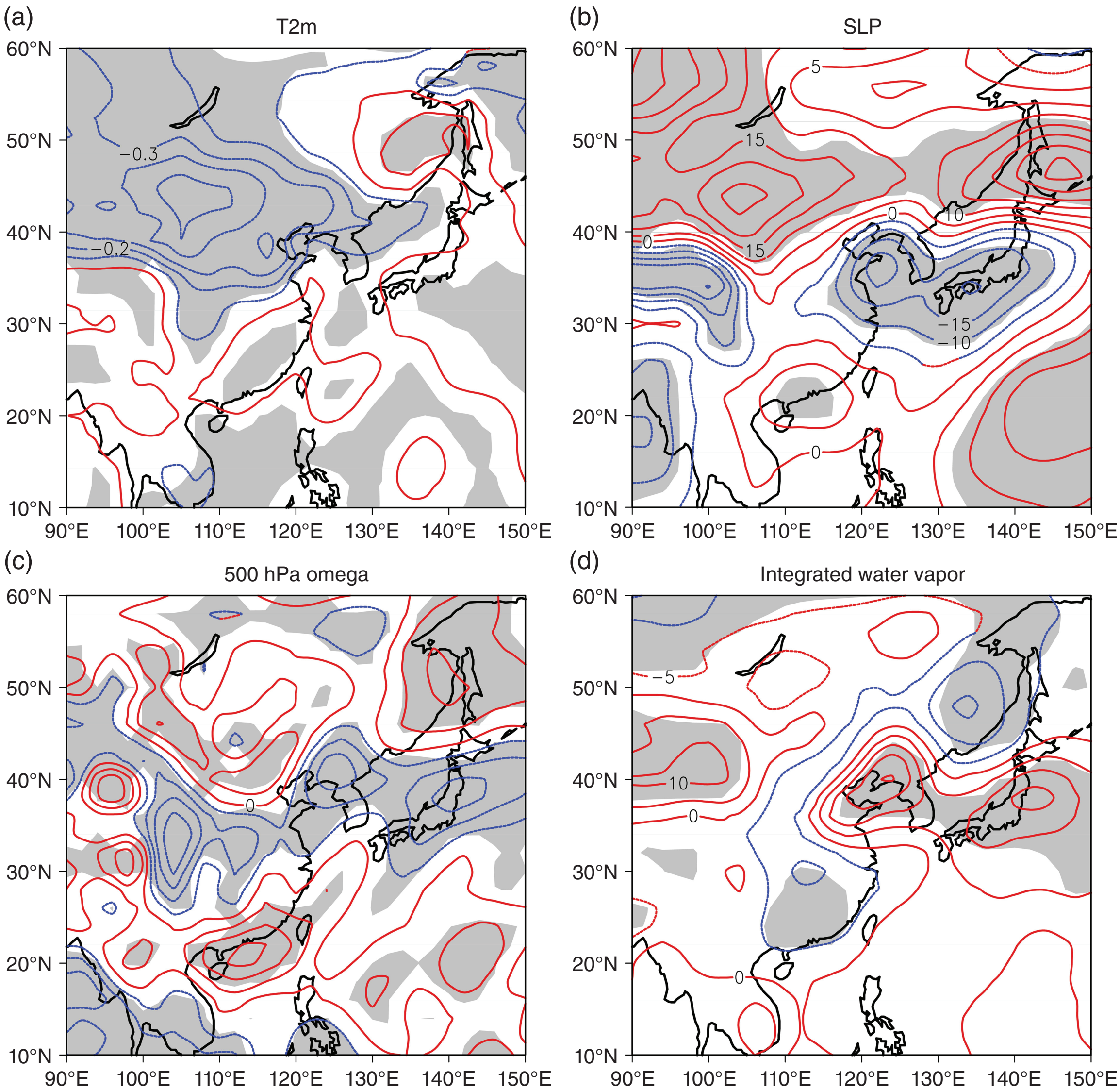

Figure 2. Regression of anomalous (a) near surface temperature (T2m, unit: °C), (b) SLP, unit: Pa, (c) 500-mb vertical velocity (ω500, scaled by 10^3, unit: hPa s^{-1}), and (d) water vapor (unit: g m^{-2}) integrated from the surface to 300-mb on the normalized NPGO index. Solid (dashed) contour denotes negative (positive) values. Shading denotes significant regression coefficient at the 95% confidence interval.

form on the southern side. These phenomena suggest that EAJS strengthens and moves northward to some extent. Consequently, the East Asian summer monsoon is strengthened, and the corresponding rain belt moves northward. Hence, the strengthened monsoon circulation transports more moisture to the northern East Asia (Figure 2(d)) and generates more precipitation over the region (Figure 1(b)). The integrated water vapor and precipitation over the central East Asian regions, such as middle and lower YRB regions, are reduced (Figure 1(b)). Previous studies also suggested that the northward displacement of EAJS is associated with the northward migration of Intertropical Convergence Zone and East Asian rain belt (Shaman and Tziperman, 2007; Gao and Yang, 2009; Ding *et al.*, 2015).

It is noteworthy that the extratropical process identified in this study are similar to the eastward propagation of so-called Silk-Road wave-train teleconnection (Ding and Wang, 2005; Hsu and Lin, 2007; Orsolini *et al.*, 2015). Lu *et al.* (2002) found that this teleconnection pattern exists in July and emerges from North Africa to East Asia along the westerly jet in the middle latitudes. Enomoto *et al.* (2003) also noticed the propagation of stationary Rossby waves along the Asian westerly jet in the upper troposphere and named it the Silk-Road pattern. Hsu and Lin (2007) identified a similar east–west wavelike pattern that connects the North Pacific and East Asia via the modification of the Eurasian jet stream. Orsolini *et al.* (2015) have investigated the role of eastward propagating wave trains across the Eurasian continent on the extreme precipitation events of summer 2010 over North and Northeast China and found a strong link between the Silk-Road wave-train along the Asian jet stream and extreme precipitation events. Besides, they also noticed a polar wave-train along the sub-polar jet. However, this polar wave-train is not reflected in NPGO in our study. Previous studies suggest that the Silk-Road wave-train is

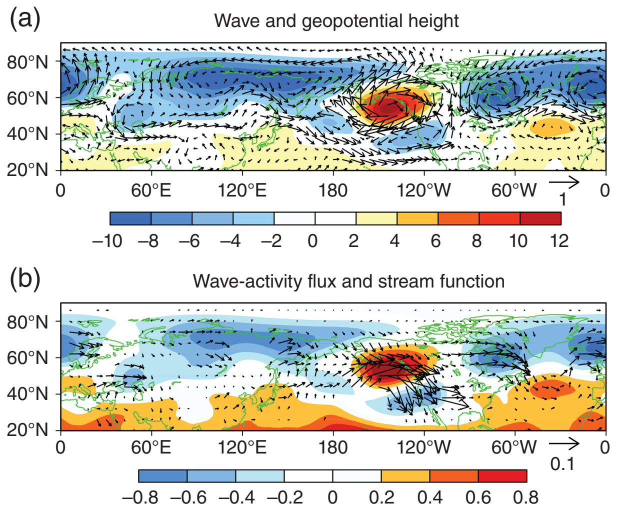

Figure 3. As Figure 2 but for (a) geopotential height (shading, unit: m) and wind (vector, unit: m s^{-1}), and (b) Plumb wave activity fluxes (vector, unit: m^2 s^{-2}) and stream function (shading, unit: m^2 s^{-1}, scaled by 10^{-6}) at the 250-mb level.

likely to be forced by transient eddies and blockings in the North Atlantic and European sector (Bothe *et al.*, 2010; Schubert *et al.*, 2014), and ENSO-related SSTA (Hsu and Lin, 2007). Our analysis results show that it may also be reflected in the NEP SSTA, e.g. the NPGO phenomenon, at a decadal scale.

4.2. Tropical process

Figure 4 depicts the spatial pattern of large-scale winds, velocity potential, and divergent wind with respect to NPGO. Anomalous high-level cyclone appears over the northern part of NEP, and anticyclone forms over the southern parts (Figure 4(a)). Anomalous low-level anticyclone and cyclone generate over the corresponding areas (Figure 4(c)). These patterns correspond to the SSTA pattern in NEP (Figure 1(c)). Low-level wind anomalies associated with NPGO resemble those associated with the Victoria Mode (Ding *et al.*, 2015). Low-level anticyclone and cyclone over the NEP induce northeasterly winds (Figure 4(c)), which induce the convergence center over the central Pacific (Figure 4(d)). This process leads to wind–evaporation–SST feedback (Xie and Philander, 1994), and the thermodynamic coupling induces positive SSTAs in the tropical central Pacific (TCP, Figure 1(c)). This coupling is also observed in the high-level atmosphere (Figure 4(c)), with a divergence center appearing over TCP.

The low-level northerly and high-level southerly divergent winds over NEP induce an anomalous meridional circulation that connects extratropical and tropical Pacific (Figure 4(b) and (d)). The meridional circulation induces positive convection over the TCP. Accordingly, this strengthened convection modifies the Walker circulation through the release of latent heat. The change in Walker circulation exhibits a zonal wave-train pattern and constructs a tropical bridge that connects NPGO and East Asia. A downward branch over the tropical western Pacific (e.g. around 150°E), an upward branch over the western side of Maritime region (e.g. around 130°E), and a downward branch over Indonesia (e.g. around 90°E) are observed from east to west. In particular, the downward branch of Walker circulation over the tropical western Pacific respectively induces northerly and southerly divergent winds at low- and high-level atmospheres over the subtropical western Pacific. Low-level northerly winds can strengthen the summer monsoon flow subtropical western Pacific. The strengthened summer monsoon circulation can thus transport more than the normal moisture from the western North Pacific to the northern East Asia, where positive precipitation anomalies occur (Figure 1(b)).

5. Summary

NPGO has played a major role in modulating the SST variability since the early 1990s (Bond *et al.*, 2003). This oscillation has also been projected to strengthen because of anthropogenic global warming (Di Lorenzo *et al.*, 2008). Therefore, the possible influences of NPGO on East Asian precipitation should be determined. In this study, MCA is used to identify the coupling relationship between global SSTA and East Asian summer precipitation. The results reveal that NPGO is the third mode modulating the decadal variation of EASP. 'Global warming' and PDO are the first two leading modes. Under the influence of NPGO, precipitation exhibits a north-to-south '+ − +' tripole pattern in East Asia.

The associated atmospheric circulations are also examined, and a sketch of the mechanisms is depicted in Figure 5. NPGO and the East Asian summer precipitation are linked via two processes, namely, extratropical and tropical processes. In the extratropical process, an eastward propagating Rossby wave is featured by NPGO and passes through North America and the Eurasian continent, and EAJS strengthens and moves more northward. In the tropical process, NPGO is associated with meridional circulation over the NEP and an anomalous Walker circulation over the tropical oceans. The latter exhibits a downward branch over the tropical western Pacific; as a result, meridional circulation over the subtropical western Pacific and anomalous low-level northerly wind are induced. The two processes strengthen the East Asian summer monsoon circulation and transport more moisture to northern East Asia. Therefore, the precipitation in northern East Asian regions is greater than normal levels; by contrast, the precipitation in central regions, such as middle and lower YRB, is less than normal levels.

Acknowledgement

This research was supported by the National Natural Science Foundation of China (numbers 41401052 and 41575078).

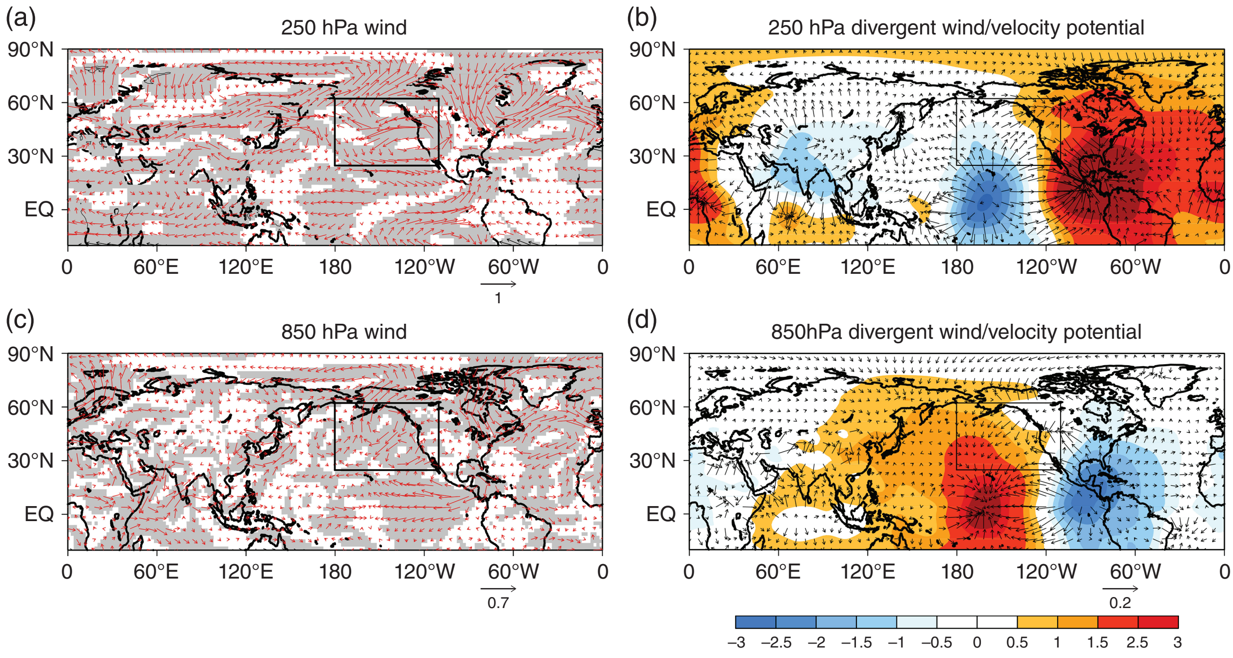

Figure 4. As Figure 2 but for large-scale winds (vector, unit: m s^{-1}), velocity potential (color shading, unit: m^2 s^{-1}, scaled by 10^5), and divergent winds (vector, unit: m s^{-1}). Box denotes the northeastern Pacific region subjected to EOF analysis on SSHA.

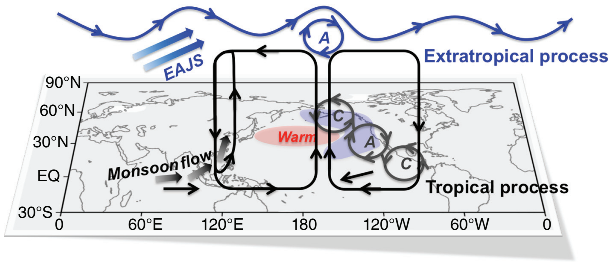

Figure 5. A sketch showing the tropical (black) and extratropical (blue) processes associated with the influences of NPGO on the East Asian summer precipitation. 'A' ('C') denotes anticyclone (cyclone). Arrow indicates the atmosphere flow. Red and blue shading denote warm and cool SST anomalies, respectively.

Supporting information

The following supporting information is available:

Figure S1. The first three leading modes of maximum covariance analysis on 5-year Butterworth low-pass filtered summer (May–September) precipitation in East Asia (105°–145°E, 20°–45°N) and filtered global sea surface temperature (SST) anomalies. (a, d, g): temporal coefficients of precipitation (blue) and SST anomaly (SSTA) (red); (b, e, h): spatial coefficients of precipitation anomaly; (c, f, i): spatial coefficients of SSTA.

References

Bond NA, Overland JE, Spillane M, Stabeno PJ. 2003. Recent shifts in the state of the North Pacific. *Geophysical Research Letters* **30**: 2183.

Bothe O, Fraedrich K, Zhu X. 2010. The large-scale circulations and summer drought and wetness on the Tibetan plateau. *International Journal of Climatology* **30**: 844–855.

Butterworth S. 1930. On the theory of filter amplifiers. *Experimental Wireless & the Wireless Engineer* **7**: 536–541.

Carton JA, Giese BS. 2008. A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). *Monthly Weather Review* **136**: 2999–3017.

Chang C, Zhang Y, Li T. 2000. Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part I: roles of the subtropical ridge. *Journal of Climate* **13**: 4310–4325.

Chhak KC, Di Lorenzo E, Schneider N, Cummins PF. 2009. Forcing of low-frequency ocean variability in the Northeast Pacific. *Journal of Climate* **22**: 1255–1276.

Choi K-S, Oh S-B, Byun H-R, Kripalani R, Kim D-W. 2011. Possible linkage between East Asian summer drought and North Pacific Oscillation. *Theoretical and Applied Climatology* **103**: 81–93.

Compo CP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RY, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ. 2011. The twentieth century reanalysis project. *Quarterly Journal of the Royal Meteorological Society* **137**: 1–28.

Di Lorenzo E, Schneider N, Cobb KM, Chhak K, Franks PJS, Miller AJ, McWilliams JC, Bograd SJ, Arango H, Curchister E, Powell TM, Rivere P. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* **35**: L08607.

Di Lorenzo E et al. 2010. Central Pacific El Niño and decadal climate change in the North Pacific Ocean. *Nature Geoscience* **3**: 762–765.

Ding Y, Chan JC. 2005. The East Asian summer monsoon: an overview. *Meteorology and Atmospheric Physics* **89**: 117–142.

Ding Q, Wang B. 2005. Circumglobal teleconnection in the Northern Hemisphere Summer. *Journal of Climate* **18**: 3483–3505.

Ding Y, Wang Z, Sun Y. 2008. Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences. *International Journal of Climatology* **28**: 1139–1162.

Ding R, Li J, Tseng Y h, Ruan C. 2015. Influence of the North Pacific Victoria mode on the Pacific ITCZ summer precipitation. *Journal of Geophysical Research: Atmospheres* **120**: 964–979.

Enomoto T, Hoskins BJ, Matsuda Y. 2003. The formation mechanism of the Bonin high in August. *Quarterly Journal of the Royal Meteorological Society* **129**: 157–178.

Gao H, Yang S. 2009. A severe drought event in northern China in winter 2008–2009 and the possible influences of La Niña and Tibetan Plateau. *Journal of Geophysical Research: Atmospheres* **114**: D24104.

He S, Wang H. 2013. Oscillating relationship between the East Asian winter monsoon and ENSO. *Journal of Climate* **26**: 9819–9838.

Hsu H-H, Lin S-M. 2007. Asymmetry of the tripole rainfall pattern during the East Asian summer. *Journal of Climate* **20**: 4443–4458.

Huang R, Chen J, Wang L, Lin Z. 2012. Characteristics, processes, and causes of the spatio-temporal variabilities of the East Asian monsoon system. *Advances in Atmospheric Sciences* **29**: 910–942.

Kaplan A, Cane MA, Kushnir Y, Clement AC, Blumenthal MB, Rajagopalan B. 1998. Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research* **103**: 18567–18589.

Kimoto M. 2005. Simulated change of the East Asian circulation under global warming scenario. *Geophysical Research Letters* **32**: L16701.

Kwon M, Jhun JG, Ha KJ. 2007. Decadal change in East Asian summer monsoon circulation in the mid-1990s. *Geophysical Research Letters* **34**: L21706.

Li J, Wu Z, Jiang Z, He J. 2010. Can global warming strengthen the East Asian summer monsoon? *Journal of Climate* **23**: 6696–6705.

Lienert F, Doblas-Reyes FJ. 2013. Decadal prediction of interannual tropical and North Pacific sea surface temperature. *Journal of Geophysical Research: Atmospheres* **118**: 5913–5922.

Lu RY, Oh JH, Kim BJ. 2002. A teleconnection pattern in upper-level meridional wind over the North African and Eurasian continent in summer. *Tellus A* **54**: 44–55.

Luo M, Leung Y, Zhou Y, Zhang W. 2015. Scaling behaviors of global sea surface temperature. *Journal of Climate* **28**: 3122–3132.

Luo M, Leung Y, Graf HF, Herzog M, Zhang W. 2016. Interannual variability of the onset of the South China Sea summer monsoon. *International Journal of Climatology* **36**: 550–562.

Orsolini YJ, Zhang L, Peters DHW, Fraedrich K, Zhu X, Schneidereit A, van den Hurk B. 2015. Extreme precipitation events over north China in August 2010 and their link to eastward-propagating wave-trains across Eurasia: observations and monthly forecasting. *Quarterly Journal of the Royal Meteorological Society* **141**: 3097–3105.

Pak G, Park Y-H, Vivier F, Kwon Y-O, Chang K-I. 2014. Regime-dependent nonstationary relationship between the East Asian winter monsoon and North Pacific Oscillation. *Journal of Climate* **27**: 8185–8204.

Pei L, Yan Z, Yang H. 2015. Multidecadal variability of dry/wet patterns in eastern China and their relationship with the Pacific Decadal Oscillation in the last 413 years. *Chinese Science Bulletin* (Chinese Version) **60**: 97.

Plumb RA. 1985. On the three-dimensional propagation of stationary waves. *Journal of the Atmospheric Sciences* **42**: 217–229.

Schneider U, Becker A, Finger P, Meyer-Christoffer A, Rudolf B, Ziese M. 2011. GPCC full data reanalysis version 6.0 at 1.0°: monthly land-surface precipitation from rain-gauges built on GTS-based and historic data. *FD_M_V6_050*.

Schubert SD, Wang H, Koster RD, Suarez MJ, Groisman PY. 2014. Northern Eurasian heat waves and droughts. *Journal of Climate* **27**: 3169–3207.

Shaman J, Tziperman E. 2007. Summertime ENSO-North African-Asian Jet teleconnection and implications for the Indian monsoons. *Geophysical Research Letters* **34**: L11702.

Von Storch H. 1999. Misuses of statistical analysis in climate research. In *Analysis of Climate Variability*, Hans von Storch, Antonio Navarra (eds). Springer: UK; 11–26.

Von Storch H, Zwiers FW. 2001. *Statistical Analysis in Climate Research*. Cambridge University Press: UK.

Wang L, Gu W. 2016. The Eastern China flood of June 2015 and its causes. *Science Bulletin* **61**: 178–184.

Wang B, Wu R, Fu X. 2000. Pacific-East Asian teleconnection: how does ENSO affect East Asian climate? *Journal of Climate* **13**: 1517–1536.

Wang L, Chen W, Huang R. 2007. Changes in the variability of North Pacific Oscillation around 1975/1976 and its relationship with East Asian winter climate. *Journal of Geophysical Research: Atmospheres* **112**: D11110.

Wang L, Chen W, Fong S, Leong K. 2011. The seasonal march of the North Pacific Oscillation and its association with the interannual variations of China's climate in boreal winter and spring. *Chinese Journal of Atmospheric Sciences* (in Chinese) **35**: 393–402.

Wu R, Wang B. 2002. A contrast of the East Asian summer monsoon-ENSO relationship between 1962–77 and 1978–93. *Journal of Climate* **15**: 3266–3279.

Xie S-P, Philander SGH. 1994. A coupled ocean-atmosphere model of relevance to the ITCZ in the eastern Pacific. *Tellus A* **46**: 340–350.

Xie S-P, 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.

Yi DL, Zhang L, Wu L. 2015. On the mechanisms of decadal variability of the North Pacific Gyre Oscillation over the 20th century. *Journal of Geophysical Research, Oceans* **110**: 6114–6129.

Yu R, Wang B, Zhou T. 2004. Tropospheric cooling and summer monsoon weakening trend over East Asia. *Geophysical Research Letters* **31**: L22212.

Zhang R. 2015. Changes in East Asian summer monsoon and summer rainfall over eastern China during recent decades. *Science Bulletin* **60**: 1222–1224.

Zhang L, Lü Q, Zhang Y. 2011. Advances in the study of North Pacific Gyre Oscillation. *Advances in Earth Science* **11**: 006.

Zhang W, Leung Y, Min J. 2013. North Pacific Gyre Oscillation and the occurrence of western North Pacific tropical cyclones. *Geophysical Research Letters* **40**: 5205–5211.

Zhou B, Xia D. 2012. Interdecadal change of the connection between winter North Pacific Oscillation and summer precipitation in the Huaihe River valley. *Science China Earth Sciences* **55**: 2049–2057.

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.