The North Pacific Gyre Oscillation and East Asian summer precipitation

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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°×1° latitude by longitude (Schneider et al., 2011). SSTA data are derived from the Kaplan SSTA dataset with a spatial resolution of 5°×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°N–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 an 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)).
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 cen-
tral 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 conver-
gence 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 influ-
encing 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 extratropi-
cal 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 geopo-
tential 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 sec-
ond EOF of SSHA in the NEP (Di Lorenzo et al.,
2008; Yi et al., 2015). This geopotential height pat-
tern also features a zonal wave-train pattern in the
high-latitude region. Figure 3(b) shows the wave activ-
ity 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 Amer-
ica, Atlantic, and the Eurasian continents and generates
intensified 250-mb geopotential height over the north-
erm East Asia (Figure 3(a)).

This given event is an extratropical process that con-
nects 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), anom-
alous 250-mb westerlies appear in the central and nor-
thern side of EAJS; conversely, easterly wind anomalies

Figure 1. Third mode of MCA on 5-year Butterworth low-pass filtered summer (May–September) precipitation in East Asia
(105°E–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.
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 and generates more precipitation over the region. The integrated water vapor and precipitation over the central East Asian regions, such as middle and lower YRB regions, are reduced. Previous studies also suggested that the northward displacement of EAJS is associated with the northward migration of Intratropical 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 2. Regression of anomalous (a) near surface temperature ($T_{2m}$; unit: °C), (b) SLP, unit: Pa, (c) 500-mb vertical velocity ($\omega_{500}$, 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.
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–SST feedback 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 from the western Pacific to northern East Asia, where positive precipitation anomalies occur.

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 EAJJS strengthens and moves more northerward. 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.

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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.

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