A 117-year long index of the Pacific-Japan pattern with application to interdecadal variability

Hisayuki Kubota, Yu Kosaka and Shang-Ping Xie

Department of Coupled Ocean-atmosphere-Land Processes Research, Japan Agency for Marine-Earth Science and Technology (DCOP, JAMSTEC), Yokosuka, Japan

Research Center for Advanced Science and Technology, The University of Tokyo, Japan

Scripps Institution of Oceanography, University of California San Diego, CA, USA

ABSTRACT: The Pacific-Japan (PJ) pattern affects interannual variability in the East Asian and western North Pacific (WNP) summer monsoons. This teleconnection pattern is characterized by a meridional dipole of anomalous circulation and precipitation between the tropical WNP and the midlatitudes. This study develops a long index of the PJ pattern using station-based atmospheric pressure data to track the PJ variability from 1897 to 2013. This index is correlated with a wide array of climate variables including air temperature, precipitation, Yangtze River flow, Japanese rice yield and the occurrence of tropical cyclones over the WNP (especially those that make landfall on the Chinese and Korean coast). For the recent three decades, the PJ index reproduces well-known correlations with El Niño-Southern Oscillation (ENSO) in the preceding boreal winter and Indian Ocean temperature in the concurrent summer. For the 117-year period, this ENSO-PJ relationship varies on interdecadal time scales, with low correlations in the 1920s and from the 1940s to 1970s, and recurrences of significant correlations at the beginning of the 20th century and the 1930s. In accordance with the modulation, the magnitude and regional climate effect of the PJ variability have changed. These results highlight the importance of interdecadal modulations of climate anomalies in the summer WNP and the need of long-term observations to study such modulations.

KEY WORDS: interannual variability; interdecadal modulations; ENSO; teleconnection; East Asian summer monsoon; western North Pacific summer monsoon

Received 13 November 2014; Revised 11 June 2015; Accepted 11 June 2015

1. Introduction

About 60% of the world’s population lives in the Asian monsoon region. Asian monsoon climate displays large variability that affects their lives. The Asian summer monsoon features pronounced seasonal changes of wind and rainfall (Ramage, 1971; Matsumoto, 1992). Thermal contrast between land and ocean contributes seasonal variations of winds in the Asian continent (Murakami and Matsumoto, 1994). During summer, moist southwesterly to westerly winds blow from the Arabian Sea, through the Bay of Bengal, South China Sea (SCS) and Philippine Sea, bringing seasonal rainfall to India, Indochina peninsula and the Philippines (Wang, 2006). The Asian summer monsoon system has several regional subsystems. Over the oceanic region in the Philippine Sea, the western North Pacific (WNP) summer monsoon dominates (Murakami and Matsumoto, 1994). Further north in midlatitude Japan, China and Korea, summer is the wet season and features a northeastward-slanted rain band called Meiyu, Changma and Baiu from June to July as the East Asian summer monsoon (Lau et al., 1988; Ninomiya and Akiyama, 1992; Sampe and Xie, 2010).

The Pacific-Japan (PJ) teleconnection pattern is a dominant pattern of interannual variability for the WNP and East Asian summer monsoons (Nitta, 1987). The PJ pattern features an anomalous dipole of lower tropospheric circulation, whose centres of action are over the Philippine Sea and the midlatitudes around Japan. In this study, we define the polarity of the PJ pattern following Nitta (1987): the positive PJ pattern is accompanied by cyclonic (anti-cyclonic) surface anomalies in the tropical (midlatitude) WNP. For the positive PJ pattern, anomalously strong convective activity over the Philippine Sea promotes a Rossby wave teleconnection poleward, forcing the anomalous circulation (Nitta, 1986, 1987, 1989; Kurihara and Tsuyuki, 1987; Kawamura et al., 1996; Kosaka and Nakamura, 2010). The associated anomalies in thermal advection in the midlatitudes suppress the Meiyu-Baiu rainfall activity (Huang and Sun, 1992; Kosaka et al., 2011) and feed back to local circulation anomalies (Lu and Lin, 2009). During the positive phase of the PJ pattern, the WNP summer monsoon activity intensifies with increased rainfall (e.g. western Indochina peninsula and the western Philippines), while the East Asian summer monsoon weakens with hot and dry summers over Japan, Korea and the Yangtze River basin (Wakabayashi and Kawamura, 2004; Yasunaka and Hanawa, 2006).

A wide array of climate variables significantly correlate with the PJ pattern in East and Southeast Asia (Figure 1),...
including Western Philippine summer rainfall, Japan summer temperature and number of tropical cyclones (TCs) that pass through Taiwan and Okinawa region. Rice yield in Japan and Yangtze River flow (before 2003 when the Three Gorges Dam became operational) is also correlated significantly. During the negative phase of the PJ pattern, by contrast, the WNP summer monsoon activity becomes weak with cool, wet summer in Japan, Korea and the Yangtze River basin due to an active East Asian summer monsoon. In a negative PJ event of 1998 summer, major floods occurred in Yangtze River, more than 3000 people died and 13.3 million houses were damaged or destroyed (Zong and Chen, 2000).

The PJ pattern is correlated with El Niño-Southern Oscillation (ENSO) in the preceding boreal winter (Yang et al., 2007; Figure 1). Xie et al. (2009) proposed a mechanism for this lingering ENSO influence on the summer WNP via Indian Ocean (IO) sea surface temperature (SST) anomalies. El Niño (La Niña) peaks in boreal winter and warms (cools) the IO via anomalous Walker circulation (Klein et al., 1999). After the equatorial Pacific SST anomalies associated with ENSO have dissipated by the following summer (2002 for Yangtze River flow). Bars are shown in grey for Yangtze River flow after Three Gorges Dam was operated in 2003. Nine-year running average has been subtracted except for the PJ index.

Figure 1. Normalized time series of the station-based PJ index (defined in Section 3), Niño 3.4 SST anomaly in DJF based on HadSST3 median (sign flipped; unit: °C), anomalous rainfall averaged for West Philippine Sea regions in JJA (unit: SD), northern Japan temperature anomaly in JJA (unit: °C), Japan rice yield anomaly per unit area (unit: SD), anomaly of JTWC TC counts in Taiwan and Okinawa regions in JJA (unit: SD) and Yangtze River flow anomaly in JJA (sign flipped; unit: SD). Positive and negative values are shown in red and blue bars, respectively. Numbers on the right side indicate correlation coefficients with the PJ index for the shown period (until 2002 for Yangtze River flow). Bars are shown in grey for Yangtze River flow after Three Gorges Dam was operated in 2003. Nine-year running average has been subtracted except for the PJ index.

The climate regime shift in the late 1970s (Xie et al., 2010). Chowdary et al. (2012) showed that the ENSO teleconnection to the Philippine Sea in the post-ENSO summers varies with the interdecadal modulation of ENSO variance. Those results suggest that seasonal predictability of the PJ pattern may also vary from a decade to another. It is unclear whether the global warming or natural variability has caused the interdecadal modulation of the WNP and East Asian summer monsoon variability. Many indices developed to identify the seasonality and interannual variability of the East Asian summer monsoon are based on reanalysis data (Wang et al., 2008a). Reliable reanalysis data sets are unavailable before 1950s and the quality is not steady due to changes in assimilated data (Wu and Xie, 2003; Wu et al., 2005). This situation has restricted investigations of the interdecadal modulation to a single regime shift in the late 1970s (Wu and Wang, 2002; Wang et al., 2008b; Xie et al., 2010) or with another recent one around 2000 (Feng et al., 2014). There needs a long index of uniform quality appropriate to examine interdecadal variability.

In this study, we define a new PJ pattern index using station-based, atmospheric pressure data to track modes of large-scale circulation, specifically the Southern Oscillation and North Atlantic Oscillation (NAO; Walker, 1924). The Southern Oscillation Index (SOI) tracks ENSO variability (Ropelewski and Halpert, 1987), and NAO explains much of the North Atlantic climate variability (Hurrel, 1995). Station data have the advantage of being continuous in time and uniform in data quality, as opposed to reanalysis that assimilate observations of varied quality and quantity.

In this study, we define a new PJ pattern index using station-based, atmospheric pressure data to represent the long-term variability of the East Asian and WNP summer monsoon. In contrast to other PJ indices using reanalysis data (Wakabayashi and Kawamura, 2004; Kosaka and Nakamura, 2010), our new PJ index has an advantage of going back to 1897 for more than 110 years with reliable quality. We examine variability of the WNP and East Asian summer monsoons in relation to the PJ pattern and show strong interdecadal modulation. The long PJ index has potential to relate the PJ pattern to historical natural disasters that occurred in East and Southeast Asia. It permits putting interdecadal modulations in a long historical perspective necessary to distinguish between global warming and natural variability.

Section 2 describes the data used in this study. Section 3 defines the new PJ index by using station pressure data. Section 4 correlates the PJ index to regional climate variability for the recent three decades, followed by a discussion of interdecadal modulations in Section 5. Section 6 is a summary with discussions.

2. Data

Table 1 lists data sets used in this study. Historical station data are collected back to 1897 in Japan and Taiwan, and 1901 in the Philippines. The station data are from the Japan...
Table 1. List of data sets used.

| Abbreviation/name              | Nomenclature/description                                      | Period used          | Horizontal resolution | Figures                  | Reference                                      |
|--------------------------------|--------------------------------------------------------------|----------------------|-----------------------|--------------------------|-----------------------------------------------|
| HadSST3                        | Hadley Centre gridded SST data set version 3                 | 1887–2012            | 5° × 5°               | Figures 1, 4(c), (d) and 6–8 | Kennedy et al. (2011)                         |
| West Philippine rainfall       | Rainfall at West Philippine 5 stations                      | 1901–2013            |                       | Figure 1                  |                                               |
| JMA temperature, pressure     | Japan Meteorological Agency station temperature and pressure in Japan | 1897–2013            |                       | Figures 1 and 9           | http://www.data.jma.go.jp/obd/stats/data/en/smp/ |
| Taiwan pressure                | Taiwan Central Weather Bureau pressure at two stations in Taiwan | 1897–2013            |                       | Figure 1                  | www.cwb.gov.tw/V7e/climate/monthly Data/md.htm|
| Japan rice yield               | Japan rice yield per unit area                               | 1897–2013            |                       | Figures 1 and 10          | www.maff.go.jp/j/tokei/kouhyou/sakumotou/sakkyou_kome/ |
| Historical TC counts          | Historical TC counts over the Taiwan-Okinawa region         | 1904–2013            |                       | Figures 1 and 11          | Kubota and Chan (2009)                        |
| Yangtze River flow            | Yangtze River flow at Yichang station                       | 1897–2010            |                       | Figure 1                  |                                               |
| JRA55                          | Japanese 55-year Reanalysis                                 | 1958–2012            | 1.25° × 1.25°         | Figures 2(a)–(c), 3       | Kohlenz, Germany                               |
| CMAP                           | U.S. Climate Prediction Center (CPC) Merged Analysis of Precipitation | 1979–2012            | 2.5° × 2.5°           | Figure 2(d)               | Xie and Arkin (1997)                           |
| ERA40                          | European Centre for Medium-range Weather Forecast (ECMWF) 40-year Reanalysis | 1958–2002            | 2.5° × 2.5°           | Figure 3                   | Uppala et al. (2005)                           |
| NCEP/NCAR                      | U.S. National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis | 1948–2012            | 2.5° × 2.5°           | Figure 3                   | Kahay et al. (1996)                            |
| 20CRv2                         | Twentieth Century Reanalysis version 2                      | 1887–2011            | 2° × 2°               | Figures 3 and 7            | Compo et al. (2011)                            |
| HadSLP2                        | Hadley Centre mean SLP data set version 2                   | 1951–2012            | 5° × 5°               | Figure 4(a) and (b)        | Allan and Ansell (2006)                        |
| ICOADS                         | International Comprehensive                                 | 1951–2012            | 2° × 2°               | Figure 4(a), (b), (c), and (f) | Woodruff et al. (2011)                        |
| OAFX                            | Ocean-atmosphere Data Set version 2.5                       | 1958–2012            | 1° × 1°               | Figure 4(g) and (h)        | Yu and Weller (2007)                           |
| APHRODITE                      | Asian Precipitation–High-Resolved Observed Data Integration Towards Evaluation version 1101 for SAT | 1951–2007 (1961–2007) | 0.5° × 0.5°          | Figure 4(c)–(f)            | Yatagai et al. (2012)                          |
| TC best track                  | Regional Specialized Meteorological Center (RSMC) Tokyo–Typhoon Center best track data | 1951–2012            | Compiled to 2.5° × 2.5° | Figure 5                  | www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-ej/RSMC_HP.htm |
| SOI                            | Southern Oscillation Index                                  | 1887–2012            | 2.5° × 2.5°           | Figures 6, 7, and 12       | Trenberth (1984)                               |

*Interpolated to 2.5° × 2.5° resolution for EOF analysis and projection onto the EOF pattern.
Meteorological Agency (JMA), Central Weather Bureau of
Taiwan, Philippine Atmospheric, Geophysical and Astro-
nomical Services Administration (PAGASA) and paper
books reported by the Central Meteorological Observatory
of Japan (CMOJ, the predecessor of JMA) and the Phi-
nipine Weather Bureau (PWB). We have chosen stations and
corrected biases by using the R-based RHtestsV4 software
(Wang and Feng, 2013a) for temperature and pressure, and
RHtests_dlyPrcp software for rainfall (Wang and Feng, 2013b).
These software products are provided by the Expert Team on Climate Change Detection and Indices
(ETCCDI) and detect discontinuities to check homogeneity.
Monthly temperature data for 1897–2013 in Japan are
from 13 stations. We have corrected atmospheric pressure data in Hengchun and Taichung, Taiwan by
removing biases of 1.73 and 2.66 hPa, respectively, before
1947 without gravity and temperature calibration (Hung,
2010). These biases were introduced due to the change of
observational agency from Japanese to Taiwanese. In the
Philippines, continuous observation was operated by PWB
until 1940, and PAGASA after 1949. Between late 1940
and 1948, Japanese and American meteorologists per-
formed observations, although there were many missing
periods due to the World War II (WWII). We do not use sta-
tion data during this period. All these station data pass
the homogeneity test. Japan rice yield and Yangtze River flow
data also satisfy the homogeneity test after normalized by
subtracting 9-year running average. For rainfall, we report
data also satisfy the homogeneity test after normalized by
homogeneity test. Japan rice yield and Yangtze River flow
periods due to the World War II (WWII). We do not use sta-
tions only surface observations of atmospheric
pressure (SLP) of HadSLP2 (Hadley Centre mean SLP
with time. As an independent check, we use sea level
pressure (SLP) of HadSST3 (Hadley Centre gridded SST
data set version 3) data set, which consists of 100 possi-
ble realizations accounting for changes in instrumenta-
tion throughout the records. There is no interpolation for this
data set, with many missing data. It is difficult to define
ENSO indices from this data set for WWII period and
before the 1910s (for the threshold of 33% spatial cover-
age to evaluate area average). We instead use SOI mainly
as an index of ENSO.

A time series of historical TC counts is based on Kubota
and Chan (2009) over the Taiwan and Okinawa region
from 1904 to 2013 obtained by combining historical TC
track data by PWB and CMOJ and recent best track data
by Joint Typhoon Warning Center (JTWC). The selected
area is within a 600 km radius from two stations (Ishigak-
ijima and Naha, Japan). For the best track data, TCs are
defined as those with maximum wind speed exceeding
17.2 m s$^{-1}$, whereas historical TCs are detected from
nearest minimum station pressure of less than 1000 hPa.
Nine stations are used to verify the TC minimum pressure
in the Taiwan and Okinawa region (Basco, Hengchun,
Taipei, Taichung, Taito, Tainan, Ishigakijima, Naha and
Naze). The latter method underestimates TC landfall
numbers in the Philippines by 13.7% compared to JTWC
for 1949–1976 (Kubota and Chan, 2009). Note that TC
counts are missing for 1940–1944.

We also use monthly gridded TC genesis and occur-
tence data set compiled from the TC best track data
for 1951–2012, obtained from the Regional Special-
ized Meteorological Center (RSMC) Tokyo-Typhoon Center.
Here, we examine TCs with wind speed exceeding
17.2 m s$^{-1}$, and define TC genesis (occurrence) as
number of TCs developed (duration in which TCs and
TC-originated extratropical cyclones are centred) within
600 km from each grid point.

Our analysis is mostly based on correlations and regres-
sions. Regressed anomalies are obtained against a unit
standard deviation (SD) of regressor. Where indicated,
we examine interdecadal modulations of interannual vari-
ability by first subtracting 9-year running mean to remove
trend and longer variations (which are identified in Deser
et al., 2004) and then evaluating 21-year running correla-
tions and regressions, with the time reported at the centre
of the 21-year window. We test statistical significance with t-test.

3. The new PJ index

An EOF analysis of 850 hPa horizontally smoothed vorticity
over the WNP (10$^\circ$–55$^\circ$N, 100$^\circ$–160$^\circ$E) during June to
August (JJA) extracts the PJ pattern as EOF1 of interannual
variability (Kosaka and Nakamura, 2010). Spatial filter for
horizontally smoothed vorticity is the same as that used in

of APHRODITE (Asian Precipitation–High-Resolved
Observed Data Integration Towards Evaluation version 1101), products based on surface measurements that suffer
less from observation quality changes. Note that HadSLP2
since 2005 is based on NCEP/NCAR.

We use SST of HadSST3 (Hadley Centre gridded SST
data set version 3) data set, which consists of 100 possi-
ble realizations accounting for changes in instrumenta-
tion throughout the records. There is no interpolation for this
data set, with many missing data. It is difficult to define
ENSO indices from this data set for WWII period and
before the 1910s (for the threshold of 33% spatial cover-
age to evaluate area average). We instead use SOI mainly
as an index of ENSO.

A time series of historical TC counts is based on Kubota
and Chan (2009) over the Taiwan and Okinawa region
from 1904 to 2013 obtained by combining historical TC
track data by PWB and CMOJ and recent best track data
by Joint Typhoon Warning Center (JTWC). The selected
area is within a 600 km radius from two stations (Ishigak-
ijima and Naha, Japan). For the best track data, TCs are
defined as those with maximum wind speed exceeding
17.2 m s$^{-1}$, whereas historical TCs are detected from
nearest minimum station pressure of less than 1000 hPa.
Nine stations are used to verify the TC minimum pressure
in the Taiwan and Okinawa region (Basco, Hengchun,
Taipei, Taichung, Taito, Tainan, Ishigakijima, Naha and
Naze). The latter method underestimates TC landfall
numbers in the Philippines by 13.7% compared to JTWC
for 1949–1976 (Kubota and Chan, 2009). Note that TC
counts are missing for 1940–1944.

We also use monthly gridded TC genesis and occur-
tence data set compiled from the TC best track data
for 1951–2012, obtained from the Regional Special-
ized Meteorological Center (RSMC) Tokyo-Typhoon Center.
Here, we examine TCs with wind speed exceeding
17.2 m s$^{-1}$, and define TC genesis (occurrence) as
number of TCs developed (duration in which TCs and
TC-originated extratropical cyclones are centred) within
600 km from each grid point.

Our analysis is mostly based on correlations and regres-
sions. Regressed anomalies are obtained against a unit
standard deviation (SD) of regressor. Where indicated,
we examine interdecadal modulations of interannual vari-
ability by first subtracting 9-year running mean to remove
trend and longer variations (which are identified in Deser
et al., 2004) and then evaluating 21-year running correla-
tions and regressions, with the time reported at the centre
of the 21-year window. We test statistical significance with t-test.

3. The new PJ index

An EOF analysis of 850 hPa horizontally smoothed vorticity
over the WNP (10$^\circ$–55$^\circ$N, 100$^\circ$–160$^\circ$E) during June to
August (JJA) extracts the PJ pattern as EOF1 of interannual
variability (Kosaka and Nakamura, 2010). Spatial filter for
horizontally smoothed vorticity is the same as that used in
Kosaka and Nakamura (2010). We have applied this EOF analysis to JRA55 regridded into a 2.5° × 2.5° resolution for 1979–2009 (Figure 2). EOF1 explains 33.5% of variance and is significantly isolated from higher modes (variance fraction of the second mode is 18.5%) based on North et al.’s (1982) rule. The same EOF analysis for unfiltered vorticity yields a similar pattern, with a lower variance fraction of 20.8%. We can obtain almost the same leading principal component (PC1) time series from EOF analysis of U.S. Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (variance fraction: 30.5%), and 850 hPa zonal wind velocity multiplied by the Coriolis parameter (35.2%), which is equivalent to meridional pressure gradient under the geostrophic balance.

Figure 2 shows the structure of the PJ pattern as regressed anomalies onto PC1. The PJ pattern features a meridional alignment of positive and negative anomalies in SLP, lower-tropospheric circulation and precipitation (Figure 2). The meridional dipole between the tropical and midlatitude WNP characterizes the PJ pattern (Nitta, 1987). Although the midlatitude positive SLP anomalies are weak due to a sector-wide SLP reduction associated with ENSO, as is discussed later. This interdecadal modulation is likely associated with changes in external forcing like ENSO, as is discussed later. Before 1960, uncertainty in reanalysis data sets and ensemble spread of 20CRv2, is also small since ~1960 when pressure observation counts became comparable with today. Yet, for many ensemble members of 20CRv2, the correlation is below the significance level before the 1960s, suggestive of interdecadal changes in structure of the PJ pattern that our station-based PJ index cannot detect well. Interestingly, the correlation is significant at the beginning of our PJ index spreads over a wide range (Figure 3(b)), high-sigificant in the mid-1930s. This interdecadal modulation is likely associated with changes in external forcing like ENSO, as is discussed later.

3.1. Correlations with other monsoon indices

We evaluate correlations of the PJ index with the projection time series of the EOF1 pattern onto major long reanalyses (Figure 3). The correlations are above the 95% confidence level after the mid-1960s. Uncertainty of observations, represented as differences between reanalysis data sets and ensemble spread of 20CRv2, is also small since ~1960 when pressure observation counts became comparable with today. Before 1960, uncertainty in reanalysis is much larger (Figure 3(a)), and its correlation with the PJ index spreads over a wide range (Figure 3(b)), highlighting the utility of our station-based PJ index. Yet, for many ensemble members of 20CRv2, the correlation is below the significance level before the 1960s, suggestive of interdecadal changes in structure of the PJ pattern that our station-based PJ index cannot detect well. Interestingly, the correlation is significant at the beginning of our PJ index: all 20CRv2 members are significant until the late 1910s and so is the ensemble mean until the mid-1910s (Figure 3(b)). Ensemble mean correlation is also significant in the mid-1930s. This interdecadal modulation is likely associated with changes in external forcing like ENSO, as is discussed later.

EOF1 features a high correlation of rainfall on Luzon Island of the northern Philippines (Figure 2(d)). There is a dominant summer rainfall maximum in the western part of Luzon Island associated with the southwesterly monsoon (Commonwealth of the Philippines, Department
of Agriculture and Commerce, 1939; Flores and Balagot, 1969). We choose five stations (Vigan, Baguio, Dagupan, Manila and Iba) located in the western Luzon. The correlation of JJA rainfall averaged for the five stations and the PJ index reaches 0.54 for 1901–2013 exceeding 99% confidence level. Thus the PJ index represents WNP summer monsoon rainfall variability for more than 100 years.

Wang and Fan (1999) proposed a WNP summer monsoon index defined as 850 hPa zonal wind shear between two domains of (5°–15°N, 90°–130°E) and (22.5°–32.5°N, 110°–140°E) in JJA. As this index well captures the tropical lobe of the PJ pattern, its correlation with our PJ index is significantly high (0.72 for 1958–2013 based on JRA55, for example). This result further supports that the tropical lobe of the PJ index is representative of the WNP summer monsoon.

4. Climate impacts

4.1. Asian summer circulation, rainfall and air temperature

Figure 4 shows surface observation anomalies regressed against the PJ index. For the recent three decades, SLP anomalies feature the meridional dipole of the PJ pattern by definition (Figure 4(a)). Consistent with Figure 2(c), land SAT and SST anomalies are also organized into a meridional dipole with anomalous warming in the midlatitude WNP and East Asia, and cooling in the tropical WNP extending into the northern IO and the Indian subcontinent (Figure 4(c)). Over East Asia and the WNP, the anomalous warm and cool regions largely overlap the rainfall decrease and increase, respectively (Figure 2(c)). The midlatitude warming is attributable to subsidence due to surface anticyclonic wind anomalies, increased insolation due to the reduced clouds (Figure 4(e)) and warm advection by surface southerlies (Figure 4(a)). Tropical SST anomalies are apparently consistent with the reduced insolation (Figure 4(e)) and increased evaporation (Figure 4(g)) and ocean mixing by increased wind speed due to anomalous westerlies (easterlies) superposed on the monsoon westerly jet over the northern IO and SCS (trade winds over the subtropical WNP; Figure 4(a)). The resultant negative local correlation between tropical convection and SST indicates that local air–sea interaction works as negative feedback to the PJ pattern (Kosaka and Nakamura, 2010; Lu and Lu, 2014).

The anomaly patterns of land precipitation and marine cloud cover (Figure 4(e)) are overall consistent with CMAP (Figure 2(d)), including negative anomalies in and around Japan, along the Yangtze River basin and in Malay Peninsula, and positive anomalies in the northern Philippines, Indochina peninsula, the tropical WNP and SCS. Figure 4(e) further reveals fine structures of rainfall anomalies in inland China, over the west coast of Luzon Island in the Philippines (as examined in Section 3.1), west...
Figure 4. Regressed anomalies against the PJ index. (a) and (b) HadSLP2 (shading) and ICOADS ocean surface wind (arrows; detrended for each period) for (a) 1977–2012 and (b) 1951–1976, (c) and (d) APHRODITE land SAT ((c) for 1977–2007 and (d) for 1961–1976) and HadSST3 median ((c) for 1977–2012 and (d) for 1951–1976), (e) and (f) APHRODITE precipitation over land ((e) for 1977–2007 and (f) for 1951–1976) and ICOADS cloudiness over ocean ((e) for 1977–2012 and (f) for 1951–1976) and (g) and (h) latent heat flux of OAFux (positive downward, (g) for 1977–2012 and (h) for 1958–1976). Stippling represents confidence level >95%. For (a) and (b), the confidence level is for SLP.
side of Annan mountain range of Indochina Peninsula, and north of Amur River. Over the Indian subcontinent, a dipolar rainfall distribution prevails (Mishra et al., 2012).

4.2. TC activity
Figure 5(a) and (c) shows the climatology (contours) and regressed anomaly (shading) of TC occurrence and genesis in JJA with respect to the PJ index. For the recent three decades, the climatological TC occurrence within 600 km radius is up to 10 days per summer over the Taiwan and Okinawa region (Figure 5(a)). PJ-associated anomalies of TC occurrence exceed 3 days in this region, reaching about 30% increase against a unit SD of the PJ index. At the positive PJ phase, TC activity increases over the East China and Yellow Seas (Choi et al., 2010; Kim et al., 2012), substantially increasing the chance of TC landfall on the eastern Chinese and Korean coast. High-resolution atmospheric model simulations can generally reproduce the pattern of interannual variability in TC occurrence, reaffirming the importance of SST forcing (Mei et al., 2015). The relative importance of random atmospheric internal variability increases for landfall TCs, however.

This change in TC occurrence is attributable to anomalies in TC genesis and tracks. The positive PJ pattern facilitates TC genesis over the tropical WNP (Figure 5(c)). Our preliminary analysis using the TC genesis potential index (Emanuel and Nolan, 2004) suggests that the lower-tropospheric vorticity increase by the PJ tropical lobe (Figures 2(a) and 4(a)) primarily contributes to TC genesis increase, reinforced (offset) on the northern (southern) flank by anomalous vertical wind shear (figure not shown). Du et al. (2011) found significant reduction of TC counts in El Niño-decay summers. We suggest that the PJ tropical lobe mediates the ENSO impact on summer TC activity over the WNP. Correlation of total TC counts in JJA over the WNP with the PJ index is 0.43 for 1977–2012 with 99% significance. In Figure 5(a), anomalous TC occurrence tends to cluster on the northwestern periphery of the climatological occurrence maximum, representing track changes due likely to northward shift of the WNP subtropical high associated with the positive PJ pattern (Figures 2(b) and 4(a)).

5. Interdecadal modulations
5.1. Relationship with ENSO
For the recent decades, the PJ index is significantly correlated with ENSO in preceding winter (Figure 1). The PJ index is correlated also with northern IO (0°–20°N, 40°–100°E) SST in concurrent JJA at −0.64 for 1979–2012. These results are consistent with the IO capacitor effect (Xie et al., 2009). Figure 6(a) and (b)
shows 21-year running correlations of the PJ index with SOI and Niño 3.4 SST in preceding boreal winter, and the northern IO SST in concurrent summer, respectively. The above-mentioned inter-basin relationships are apparent since around the 1980s. In contrast, IO and WNP climates have been changed in mid 1970s (Nitta and Yamada, 1989), these relationships are not clear from the 1940s to 1970s (Xie et al., 2010; Chowdary et al., 2012). Interestingly, a positive correlation with SOI and a negative correlation with northern IO SST were significant again prior to the 1910s and around the 1930s (Figure 6(a) and (b)), indicating that the relationships of ENSO, IO SST and the PJ pattern were active. Similar interdecadal modulations are confirmed from the projection time series of 20CRv2, but with large uncertainty before the 1960s (Figure 7).

These interdecadal changes in ENSO-PJ relationship look synchronous to the Pacific Decadal Oscillation (PDO; Mantua et al., 1997). This result motivates us to divide our data before and after 1976/1977 in Figures 4 and 5 and divide into four periods: 1897–1918, 1919–1946, 1947–1976 and 1977–2012 in Figure 8. Consistent with Figure 6(a), La Niña signal in preceding winter and IO cooling in concurrent summer are clear in 1977–2012 (Figure 8(g) and (h)) but are missing in 1947–1976 (Figure 8(e) and (f)). During 1897–1918, regressions capture the preceding La Niña and concurrent IO cooling (Figure 8(a) and (b)). For 1919–1946, the equatorial Pacific is cooler but with no significant IO cooling in preceding winter (Figure 8(c)), while northern IO is significantly cooler in concurrent summer (Figure 8(d)) associated with the PJ pattern.

Figure 6(c) examines interdecadal changes of northern IO SST anomalies in boreal summer induced by ENSO. It reveals strong northern IO cooling in JJA of ENSO-decay year around the 1900s, 1930–1940s and 1980–1990s.
Except the 1940s, these periods roughly match those with the significant PJ-ENSO correlation (Figure 6(a) and (b)). This result suggests that the amplitude of the persistent northern IO SST anomalies induced by ENSO is a key to the modulation of ENSO-PJ correlation (Kawamura et al., 1998), consistent with the IO capacitor mechanism. Yet in the late 1940s, the IO anomalies are rather strong but PJ-ENSO correlation is missing, possibly due to poor data coverage of SST during and immediately after the WWII (Chowdary et al., 2012).

For the recent three decades, the PJ pattern is correlated with cool anomalies over the eastern equatorial Pacific in concurrent summer (Figure 8(h)), whereas for 1897–1918, a warming is detected (Figure 8(b)). These anomalies suggest a weak association between the PJ pattern and developing ENSO, although the PJ index is not significantly correlated with SOI in subsequent DJF throughout the record (figure not shown). Interdecadal differences are also found in tropical Atlantic SST (Figure 8). Further analyses are needed.

After 2000, the relationships between ENSO and the PJ index weaken (Figure 6(a) and (b)) possibly due to the phase shift of PDO (McPhaden and Zhang, 2004; Dai et al., 2015) and interannual ENSO activity. This change is consistent with weak northern IO SST anomalies in ENSO-decay summer (Figure 6(c)). If the trend continues, we may again face an era of low PJ-ENSO correlation and thereby low seasonal predictability over the summer WNP and East Asia.

5.2. The 1976/1977 climate regime shift

For the last two epochs of Figure 8, many reliable observations are available for in-depth studies. Figure 4 compares structure of PJ surface anomalies before and after the 1976/1977 climate regime shift (i.e. PDO phase transition; Nitta and Yamada, 1989). The meridional SLP and rainfall dipoles are common to both epochs before and after the regime shift (Figure 4(a), (b), (e), and (f)), and so is midlatitude warming (Figure 4(c) and (d)). However, the cyclonic anomalies and cloud increase in the tropical WNP are rather weaker before the regime shift (Figure 4(b), (f), and (h)). As a result, SST cooling over the SCS and tropical WNP is also weaker (Figure 4(d)). This is related to the lack of SST cooling over the northern IO (Figure 4(d)). Kosaka et al.’s (2013) model experiment shows that the PJ pattern gains larger loading in its tropical lobe when forced by ENSO and tropical IO SST anomalies. The PJ pattern in the preregime shift epoch is not so much forced by ENSO (Figures 6(a), (b) and 8(e), (f)) but more a mode of atmospheric internal variability. Meanwhile, the midlatitude anticyclonic anomaly centre is shifted eastward in the preregime shift epoch (Figure 4(b)). The same EOF analysis as performed for Figure 2 but applied to 1948–1976 NCEP/NCAR reanalysis yields a pattern similar to Figure 4(b), with an eastward expansion of the midlatitude lobe and weak tropical anomalies (figure not shown), supporting the structural change of the PJ pattern.

Our definition of the PJ structure and the PJ index is based on the epoch when ENSO influence is large
Figure 8. Regressed anomalies of HadSST3 median in (left) preceding DJF and (right) concurrent JJA with respect to the PJ index for (a) and (b) 1897–1918, (c) and (d) 1919–1946, (e) and (f) 1947–1976 and (g) and (h) 1977–2012. Values are shown if data at each grid point are available for more than 50% of years with at least 1 month per season. SST has been detrended for each period beforehand. Stippling indicates confidence level >90%.

(i.e. after the regime shift). The structural change due to weaker ENSO influence in the pre-regime shift epoch is manifested as low correlations of the PJ index with the PJ projection time series in Figure 3(b).

The structural change of the PJ pattern suggests that its impact on TC activity also changed. Indeed, TC genesis and occurrence associated with the PJ pattern significantly altered across the regime shift (Figure 5). For 1951–1976, TC genesis is suppressed around ~140°E over the tropical WNP in the positive PJ summers (Figure 5(d)). In net, correlation between basin-wide TC occurrence and the PJ index was much lower than the postregime shift era (to be revisited in Section 5.5).

5.3. Japan summer temperature

Long temperature records are available in Japan. Figure 9 examines interdecadal modulations of JJA temperature correlation with the PJ index in northern, eastern, and western Japan and Southwest Islands of Japan. The correlations are significantly positive in northern, eastern, and western Japan and negative in Southwest Islands for the recent decades, consistent with Figure 4(c). We can trace the significant correlations back to the mid- to late 1960s. The correlations were weaker from the 1910s to 1950s, with a marginally significant correlation for northern Japan and Southwest Islands in the 1930s and for all regions before the 1910s (Figure 9). The interdecadal change appears to follow the PJ-ENSO relationship (Figure 6), suggesting that when the ENSO influence is strong, the PJ influence on temperature in Japan stands out from noise.

5.4. Rice yield in Japan

Rice is a staple food in Asian countries. An important factor for rice harvest is sunshine duration, which is correlated positively with the PJ pattern in the main island of Japan (Figure 4(e)). Indeed, rice product per unit area in Japan is significantly correlated with the PJ index for the recent four decades (Figure 1). The correlation is lower before the late 1960s but again significant before the 1920s as well as since the late 1960s (Figure 10). Despite that rice yield is also related to improved agriculture technology and the policy of rice production, the interdecadal modulation of its correlation with the PJ index is apparent for the recent decades.

5.5. Tropical cyclone

Association of the PJ pattern and TC counts in Taiwan and Okinawa region varies in interdecadal time scale (Figure 11). Consistent with Figure 5, the TC occurrence was less correlated with the PJ index in the 1960s and 1970s than thereafter, a change synchronous with the regime shift. The weak correlation before the regime shift is consistent with weak lower-tropospheric cyclonic anomalies in the PJ tropical lobe (Figure 4(b)). ENSO is known to be correlated with the TC activity over the WNP. TC activity enhances in El Niño-developing summers and autumns (Wang and Chan, 2002; Kubota and Wang, 2009) and weakens in El Niño-decaying summers (Du et al., 2011) over the WNP. In Figure 11, the correlation between ENSO and the TC counts in the Taiwan and Okinawa region becomes high when the ENSO-PJ relationship is
variability over the IO-WNP sector (Kosaka et al., 2012) that is often coupled to SST is an atmospheric mode (Kosaka and Nakamura, 2010; Nakamura and Hirota, 2014). The PJ pattern over the WNP is especially large. The PJ effect on TC landfalls on the Chinese and Korean coast is especially large. The PJ pattern is a meridional teleconnection pattern that dominates the summer WNP. This study proposes a long-term index based on station data to track the PJ pattern from 1897 to 2013. The PJ index is correlated with a wide array of variables including precipitation and air temperature in summer Southeast and East Asia, Yangtze River flow, rice yield in Japan and summer TC activity in the Taiwan-Okinawa region by changing the lower-tropospheric circulation and vertical wind shear over the WNP. Even when the ENSO-PJ association is loose, the PJ pattern can still affect the TC activity depending on intensity of its tropical circulation anomalies.

6. Summary and discussions

The PJ pattern is a meridional teleconnection pattern that dominates the summer WNP. This study proposes a long-term index based on station data to track the PJ pattern from 1897 to 2013. The PJ index is correlated with a wide array of variables including precipitation and air temperature in summer Southeast and East Asia, Yangtze River flow, rice yield in Japan and summer TC activity over the WNP. The PJ effect on TC landfalls on the Chinese and Korean coast is especially large. The PJ pattern is an atmospheric mode (Kosaka and Nakamura, 2010; Hirota and Takahashi, 2012) that is often coupled to SST variability over the IO-WNP sector (Kosaka et al., 2013). External forcing, such as ENSO, can trigger the mode and enhance the PJ variability. The coupling with IO explains why WNP-East Asian climate anomalies are prominent in the post-ENSO summer.

The 117-year long PJ index reveals that the relationship with ENSO has varied on interdecadal time scales. While the PJ pattern is significantly correlated with ENSO in the preceding boreal winter from the 1970s to 1990s, this relation vanished from the 1950s to early 1970s (Wu and Wang, 2002; Wang et al., 2008b; Xie et al., 2010; Chowdary et al., 2012). Further back in time, we find that the PJ-ENSO correlations were significant prior to the 1910s and around 1930 (Figure 6). This interdecadal variation strongly suggests that the natural interdecadal variability, rather than the global warming (Zheng et al., 2011), is the primary cause of the changes in relationship of ENSO and the PJ pattern, although aerosol-induced climate change may have an effect (Lau and Kim, 2006; Bollasina et al., 2011). As ENSO can be a major driver of the PJ pattern, the PJ variance is high when the PJ-ENSO correlation and ENSO variance are high (Figure 12; Kawamura et al., 1998). To the extent that the association of ENSO and the PJ pattern is the physical basis for seasonal prediction over the summer WNP (Chowdary et al., 2010; Kosaka et al., 2013), the PJ predictability is likely to vary from a decade to another. Interestingly, the correlation between the PJ index and a reanalysis (20CRv2)-based PJ projection time series (Figure 3(b)) displays interdecadal modulations similar to those of the ENSO-PJ relationship (Figure 6(a)) with peaks before 1910, in the mid-1930s and the 1990s. These modulations appear to be associated with structural changes of the PJ pattern. The synchronization of the two correlation time series suggests that the PJ structure varies in accordance with the ENSO forcing. Indeed, model experiments by Kosaka et al. (2013) showed that structure and tropical magnitude of the PJ pattern vary somewhat in accordance with the tropical SST influence (Section 5.2). The recent decrease of the correlation between the PJ index and PC1 time series (Figure 3(b)) is likely due to the weakening of the relationships between ENSO and the PJ index (Figure 6(a) and (b)). Some of the major natural disasters are attributable to PJ events. Devastating floods along Yangtze River occurred in 1998 in the negative phase of PJ pattern. Indeed the relationship of the PJ index with Yangtze River flow is active since the 1980s (Figure 1). Major rice harvest failure in Japan occurred in 1980, 1993 and 2003, all in the negative PJ years (Figure 1). The record harvest failure in
1993 forced the Japanese government to open the domestic rice market (Hosoe, 2004). This correlation was significant also around the 1910s (Figure 10). A historic riot took place in Japan in 1897, a year of poor rice yield and a negative PJ event. These events illustrate a potential of our PJ index for wide applications.

Acknowledgements

HK and YK contributed equally. We wish to thank Dr. Mong-Ming Lu of Central Weather Bureau of Taiwan for Taiwan station data, Dr. Esperanza O. Cayanan, Dr. Flaviana D. Hilario and Dr. Vicente B. Malano for providing Philippine Atmospheric, Geophysical and Astronomical Services Administration station data, Prof. Jun Matsumoto of Tokyo Metropolitan University, Dr. Ikumi Akasaka of Senshu University and Prof. Masumi Zaiki of Seikei University for Philippine Weather Bureau station data and Mr. Yoshio Shinohara of JMA for sharing the historical bulletins of Central Meteorological Observatory of Tokyo, Japan. HK was supported by ‘Global Environment Research Fund from the Ministry of the Environment Japan’ B-061, ‘Data Integration & Analysis System’, ‘Green Network of Excellence’ (GRENE), ‘Program for Risk Information on Climate Change’ (SOUSEI), and Grant-in-Aid for Scientific Research No. 25282085, (20240075, 23240122, and 26220202; Leader: Prof. Jun Matsumoto) and Young Scientific Research No. 15H05466 funded by MEXT and by the Japanese Ministry of Environment through the Environment Research and Technology Development Fund 2–1503; and SPX by U.S. National Science Foundation.

References

Allan R, Ansell T. 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850–2004. J. Clim. 19: 5816–5842.
Bollasina MA, Ming Y, Ramaswamy V. 2011. Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science 334: 502–505, doi: 10.1126/science.1204994.
Choi K-S, Wu C-C, Cha E-J. 2010. Change of tropical cyclone activity by Pacific-Japan teleconnection pattern in the western North Pacific. J. Geophys. Res. 115: D19114, doi: 10.1029/2010JD013866.
Chowdary JS, Xie S-P, Lee J-Y, Kosaka Y, Wang B. 2010. Predictability of summer northwest Pacific climate in 11 coupled model hindcasts: local and remote forcing. J. Geophys. Res. 115: D22121, doi: 10.1029/2010JD014595.
Chowdary JS, Xie S-P, 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. J. Clim. 25: 1722–1744.
Commonwealth of the Philippines, Department of Agriculture and Commerce. 1939. Climate of the Philippines. Bureau of Printing: Manila, Philippines, 31 pp.
Compo GP et al. 2011. The twentieth century reanalysis project. Q. J. R. Meteorol. Soc. 137: 1–28.
Dai A, Fyje JC, Xie S-P, Dai X. 2015. Decadal modulation of global surface temperature by internal climate variability. Nat. Clim. Chang. 5. doi: 10.1038/nclimate2605.
Deser C, Phillips AS, Hurrell JW. 2004. Pacific interdecadal climate variability: linkage between the tropics and the north Pacific during boreal winter since 1900. J. Clim. 17: 3109–3124.
Du Y, Yang L, Xie S-P. 2011. Tropical Indian Ocean influence on Northwest Pacific tropical cyclones in summer following strong El Niño. J. Clim. 24: 315–322.

© 2015 The Authors. International Journal of Climatology published by John Wiley & Sons Ltd Int. J. Climatol. 36: 1575–1589 (2016) on behalf of the Royal Meteorological Society.
Ebita A, Kobayashi S, Ota Y, Moriya M, Kubame R, Onogi K, Harada Y, Yaou S, Miyaoka K, Tsuchaki K, Kamahori H, Kobayashi C, Endo H, Soma M, Oikawa Y, Ishimizu T. 2011. The Japanese 55-year reanalysis ‘JRA-55’: an interim report. SOLA 7: 149–152.

Emmanuel KA, Nolan DS. 2004. Tropical cyclone activity and global climate. In 26th Conference on Hurricanes and Tropical Meteorology, Miami, FL, American Meteorological Society, Boston, MA, pp. 240–241.

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? J. Clim. 27: 2682–2698.

Flores JP, Halagat VF. 1969. In glory. Branch, Ed., Climate of the Philippines. In Climates of Northern and Eastern Asia, World Survey of Climatology, Vol. 8, Arakawa H (ed). Elsevier: Amsterdam, 159–213.

Hiroti N, Takahashi M. 2012. A triporal pattern as an internal mode of the East Asian summer monsoon. Clim. Dyn. 39: 2219–2238.

Hoos N. 2004. Crop failure, price regulation, and emergency imports of Japan’s rice sector in 1993. Appl. Econ. 36: 1051–1056.

Huang R, Sun F. 1992. Impacts of the tropical western Pacific on the East Asian summer monsoon. J. Meteor. Soc. Jpn. 70: 243–256.

Hung C-Y. 2010. New Taiwan Climate Maps 2010. National Taiwan Normal University Geography Publishing; Taipei, Taiwan, 168 pp.

Hurrel JW. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676–679.

Kalnay E. 1989. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77: 437–471.

Kawamura R, Murakami T. 2014. Summer monsoon over the Asian continent and western North Pacific. J. Meteor. Soc. Jpn. 72: 719–745.

Kawamura R, Matsumoto J. 1994. Summer monsoon over the Asian continent and the East Asia. J. Meteor. Soc. Jpn. 70: 467–495.

Kim T. 1985. Long-term variations of cloud amount in the western Pacific region. J. Meteor. Soc. Jpn. 64: 373–390.

Kita T. 1987. Convective activities in the tropical western Pacific and their impacts on the Northern Hemisphere summer circulation. J. Meteor. Soc. Jpn. 65: 165–171.

Kita T. 1989. Global features of the Pacific-Japan oscillation. J. Meteorol. Atmos. Phys. 41: 5–12.

Kita T, Yamada S. 1989. Recent warming of tropical sea surface temperature and its relationship to the northern hemisphere circulation. J. Meteor. Soc. Jpn. 67: 375–395.

Kurihara K, Tsuyuki T. 1987. Development of the barotropic high around Japan. J. Meteor. Soc. Jpn. 65: 777–802.

Kurihara K, Tsuyuki T. 1987. Development of the barotropic high around Japan and its association with Rossby wave-like propagations over the North Pacific: analysis of August 1984. J. Meteor. Soc. Jpn. 65: 237–246.

Lau K-M, Kim K-M. 2006. Observational relationships between aerosol and Asian monsoon rainfall, and circulation. Geophys. Res. Lett. 33: L21810, doi: 10.1029/2006GL027546.

Lau K-M, Yang GJ, Shen SH. 1988. Seasonal and interannual variability of summer precipitation over East Asia. J. Clim. 2: 5435–5453.

Lau K-M, Yang GJ, Shen SH. 1988. Seasonal and interannual variability of summer precipitation over East Asia. J. Clim. 2: 5435–5453.

Matsumoto K. 1992. The seasonal changes in Asian and Australian monsoon regions. J. Meteorol. Soc. Jpn. 70: 257–273.

McPhaden MJ, Zhang D. 2004. Pacific Ocean circulation rebounds. Geophys. Res. Lett. 31: L18301.

Meng W, Xie S-P, Zhao M, Wang Y. 2015. Forced and internal variability of tropical cyclone track density in the western North Pacific. J. Clim. 28: 143–167.

Mishra V, Smoliak BV, Lettenmaier DP, Wallace JM. 2012. A prominent pattern of year-to-year variability in Indian Summer Monsoon Rainfall. Proc. Natl. Acad. Sci. U. S. A. 109: 7213–7217.

Murakami T, Matsumoto J. 1994. Summer monsoon over the Asian continent and western North Pacific. J. Meteor. Soc. Jpn. 72: 719–745.

Ninomiya K, Akiyama T. 1992. Multi-scale features of Baiu, the summer rainfall in Japan. J. Meteor. Soc. Japan. 70: 467–495.

Nitta T. 1986. Long-term variations of cloud amount in the western Pacific region. J. Meteor. Soc. Jpn. 64: 373–390.

Nitta T. 1987. Convective activities in the tropical western Pacific and their impacts on the Northern Hemisphere summer circulation. J. Meteor. Soc. Jpn. 65: 165–171.

Nitta T. 1989. Global features of the Pacific-Japan oscillation. J. Meteorol. Atmos. Phys. 41: 5–12.

Nitta T, Yamada S. 1989. Recent warming of tropical sea surface temperature and its relationship to the northern hemisphere circulation. J. Meteor. Soc. Jpn. 67: 375–395.

North GR, Bell TL, Cahalan RF, Moeng FJ. 1982. Sampling errors in the estimation of empirical orthogonal functions. Mon. Weather Rev. 110: 699–706.

Ramage CS. 1971. Monsoon Meteorology. Academic Press, 296 pp.

Ropelewski CF, Halpert MS. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. Mon. Weather Rev. 115: 1606–1626.

Saito T, Xie S-P. 2010. Large-scale dynamics of the meiyu–baiu rainband: environmental forcing by the westerly jet. J. Clim. 23: 113–134.

Trenberth KE. 1984. Signal versus noise in the Southern oscillation. Mon. Weather Rev. 112: 326–332.

Uppala SM et al. 2005. The ERA-40 reanalysis. Q. J. R. Meteorol. Soc. 131: 2961–3012.

Wakabayashi S, Kawamura R. 2004. Extraction of major teleconnection patterns possibly associated with the anomalous summer climate in Japan. J. Meteor. Soc. Jpn. 82: 1577–1588.

Walker GT. 1924. Correlation in seasonal variations of weather IX: a further study of world weather. Mem. Indian Meteor. Dept. 24: 275–332.

Wang B. 2006. The Asian Monsoon. Springer Praxis Publishing, 787 pp.

Wang B. 2014. How strong ENSO events affect tropical storm activity over the western North Pacific. J. Clim. 27: 1643–1658.

Wang B, Fan Z. 1999. Choice of South Asian monsoon indices. Bull. Am. Meteorol. Soc. 80: 629–638.

Wang XL, Feng Y. 2013a. RHIvstv4 User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, 28 pp. http://etccdi.pacificclimate.org/software.shtml (accessed 29 June 2015).

Wang XL, Feng Y. 2013b. RHivstv4 Prep User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, 17 pp. http://etccdi.pacificclimate.org/software.shtml (accessed 29 June 2015).

Wang B, Wu Z, Li J, Liu J, Chang C-P, Ding Y, Wu G. 2008a. How to measure the strength of the East Asian summer monsoon. J. Clim. 21: 4449–4463.

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

Wang XL, Chen H, Wu Y, Feng Y, Pu Q. 2010. New techniques for detection and adjustment of shifts in daily precipitation data series. J. Appl. Meteorol. Climatol. 49: 2416–2436, doi: 10.1175/2010JAMC2376.1.

Wang B, Xiang B, Lee J-Y. 2013. Subtropical high predictability established a promising way for monsoon and tropical storm predictions. Proc. Natl. Acad. Sci. U. S. A. 110: 2718–2722.

Woodruff SD et al. 2011. ICOADS Release 2.5: extensions and enhancements to the surface marine meteorological archive. Int. J. Climatol. 31: 951–967.

Wu R, Wang B. 2002. A contrast of the East Asian summer monsoon–ENSO relationship between 1962–77 and 1978–93. J. Clim. 15: 3266–3279.
Wu R, Xie S-P. 2003. On equatorial Pacific surface wind changes around 1977: NCEP-NCAR reanalysis versus COADS observation. *J. Clim.* **16**: 167–173.

Wu R, Kinter JL III, Kirtman BP. 2005. Discrepancy of interdecadal changes in the Asian region among the NCEP-NCAR reanalysis, objective analysis and observations. *J. Clim.* **18**: 3048–3067.

Xie P, Arkin PA. 1997. Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Am. Meteorol. Soc.* **78**: 2539–2558.

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. *J. Clim.* **22**: 730–747.

Xie S-P, Du Y, Huang G, Zheng X-T, Tokinaga H, Hu K, Liu Q. 2010. Decadal shift in El Niño influences on Indo-western Pacific and East Asian climate in the 1970s. *J. Clim.* **23**: 3352–3368.

Yang J, Liu Q, Xie S-P, Liu Z, Wu L. 2007. Impact of the Indian Ocean SST basin mode on the Asian summer monsoon. *Geophys. Res. Lett.* **34**: L02708, doi: 10.1029/2006GL028571.

Yasunaka S, Hanawa K. 2006. Interannual summer temperature variations over Japan and their relation to large-scale atmospheric circulation field. *J. Meteor. Soc. Jpn.* **84**: 641–652.

Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A. 2012. APHRODITE: constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bull. Am. Meteorol. Soc.* **93**: 1401–1415.

Yu L, Weller RA. 2007. Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global oceans. *Bull. Am. Meteorol. Soc.* **88**: 527–539.

Zheng X-T, Xie S-P, Liu Q. 2011. Response of the Indian Ocean basin mode and its capacitor effect to global warming. *J. Clim.* **24**: 6146–6164.

Zong Y, Chen X. 2000. The 1998 flood on the Yantze, China. *Nat. Hazards* **22**: 165–184.