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Decadal change in relationship between east Asian and WNP summer monsoons

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[1] It has been recognized that the intensity of the east Asian (EA) summer monsoon has a negative correlation with that of the western North Pacific (WNP) summer monsoon. Here we show that this relationship is much stronger in the recent decade (1994–2004) than in the epoch before 1994 (1979–1993). The first two leading modes of summer-mean precipitation over the large region of the WNP and EA region are shown to be associated with two factors: the ENSO development and the WNP summer monsoon fluctuation. The leading mode has changed from an ENSO-related mode in 1979–1993 to a WNP summer monsoon-related mode in the recent decade (1994–2004). The summer-mean mid-tropospheric geopotential heights that are correlated with the WNP monsoon index also show a marked change in the teleconnection (wave-train) pattern between 1994–2004 and 1979–1993. All together this evidence suggests that the relationship between the EA and the WNP summer monsoons has experienced a significant decadal change around 1993–1994. **Citation:** Kwon, M., J.-G. Jhun, B. Wang, S.-I. An, and J.-S. Kug (2005), Decadal change in relationship between east Asian and WNP summer monsoons, *Geophys. Res. Lett.*, *32*, L16709, doi:10.1029/2005GL023026.

1. Introduction

[2] Monsoon circulation plays an important role in the earth's hydrological cycle. There are three distinguished summer monsoon subsystems in the Asian-Pacific region. They are the East Asian (EA), the western North Pacific (WNP), and the Indian summer monsoons [e.g., *Wang and LinHo*, 2002]. The EA summer monsoon is associated with the Chinese Mei-yu, the Korean Changma, and the Japanese Baiu. Year-to-year variations of the large-scale summer monsoon in the Asian-Pacific region, like seasonal march, represent strong signals of the Earth's climate system [e.g., *Wang et al.*, 2001]. Prediction of the interannual variability of the Asian-Pacific summer monsoon is a topical issue. There are numerous research works that attempt to quantify interannual variations of the monsoon intensity in summertime [*Webster and Yang*, 1992; *Goswami et al.*, 1999; *Wang and Fan*, 1999]. *Wang and Fan* [1999] suggested two major circulation indices to measure the variability of the Indian and the WNP summer monsoons, respectively. In particular, the WNP monsoon index (WNPMI) reflects not only the dominant mode in low-level monsoon circulation but also the rainfall variability over the South China Sea and the Philippine Sea [*Wang et al.*, 2001], which will be used in this study.

[3] Rainfall anomalies associated with the monsoon front of the northeastern Asia region including northeastern China, Korea, and Japan are simultaneously correlated with convective activity over the vicinity of the Philippines in summertime [*Nitta*, 1987; *Huang and Sun*, 1992]. *Nitta* [1987] suggested that the PJ (Pacific Japan) teleconnection pattern originated from a barotropic response to the WNP latent heating forcing. Summer-mean precipitation anomaly over the northeastern Asian region exhibits a tendency to be negatively correlated with the intensity of the WNP summer monsoon.

[4] There are remarkable differences in summertime circulation between 1993 and 1994 [e.g., *Park and Schubert*, 1997; *Geng et al.*, 2000; *Yoo et al.*, 2004]. Central China, Korea, and Japan experienced severe heat and drought conditions during the summer of 1994 and an extremely cool and wet summer in 1993. In particular, *Park and Schubert* [1997] have suggested that the anomalous circulation over east Asia in summer of 1994 was primarily the result of orographic forcing associated with zonal wind changes over the Tibetan Plateau.

[5] Lack of long-term satellite estimation of the precipitation has left study of decadal change in the EA and WNP summer monsoons which is a research-void area. The aim of this study is to show observational evidence for decadal changes in the relationship between the EA and WNP summer monsoons. In particular, we will show distinguishable changes in the summer monsoon circulation over east Asia and the WNP in the period before and after the mid-1990s. We will also show significant changes of the several mean fields in the mid-1990s.

2. Data and Methods

[6] The Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP [*Xie and Arkin*, 1997]) dataset, with 2.5 by 2.5 degree spatial resolution, was used for the period from 1979 to 2004. The global precipitation dataset, which covers the ocean, is based on the gauge observations and the satellite estimates. The National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis [*Kalnay et al.*, 1996] currently provides atmospheric data for the period 1948–2004. The data used in this study include geopotential height at 500 hPa, and zonal and meridional winds at 200 hPa and 850 hPa, respectively. The monthly means of these data have been interpreted into a grid with a horizontal resolution of 2.5 degree by 2.5 degree. The National

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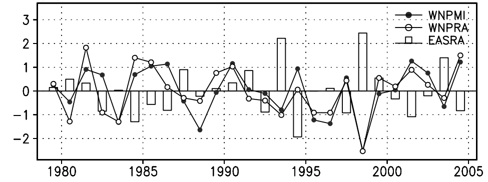
(a) WNPMI, WNPRA, and EASRA



(b) SLIDING CORR(WNPMI or WNPRA, EASRA)

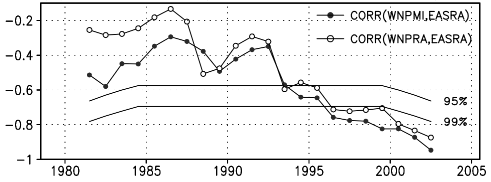


Figure 1. (a) Normalized WNPMI (WNP Monsoon Index), WNPRA (WNP Rainfall Anomaly), and EASRA (East Asian Summer Rainfall Anomaly) are represented by closed circles, open circles, and bars, respectively. (b) Sliding correlation coefficients between WNPMI and EASRA in a closed circle (WNPRA and EASRA in an open circle) with a window of 11 years. Horizontal solid lines are denoted by 95% and 99% confidence level, respectively.

Oceanic and Atmospheric Administration (NOAA) optimal interpolation sea surface temperature (OI SST [*Reynolds and Smith*, 1994]) monthly mean data were also used. The dataset is 1.0 degree by 1.0 degree in horizontal resolution.

[7] Since the rainfall datasets only cover a short time period, careful analysis is required to obtain information of statistical significance. Here, we used the Lepage test [*Lepage*, 1971; *Yonetani and McCabe*, 1994]. The Lepage test is a non-parametric test that investigates significant differences between two samples, even if the distributions of the parent populations are unknown. The Lepage statistic, HK (symbol used by *Yonetani and McCabe* [1994]), is a combination of standardized Wilcoxon's and Ansari-Bradley's statistic [*Lepage*, 1971]. If HK is greater than 5.99 or 9.21, the mean change between the two samples is significant at 95% or 99% confidence level, respectively.

[8] For convenience, three indices were used to quantify the WNP and EA summer monsoons. Three indices used in this study are described as follows. The WNPMI [*Wang et al.*, 2001] was used as representing the WNP summer monsoon. WNPMI is an index based on circulation, defined by the differences in area-averaged 850 hPa zonal wind between the area (5N–15N, 100E–130E) and (20N–30N, 110E–140E). WNPRA (WNP Rainfall Anomaly) was also used to compare with the WNPMI and the rainfall anomaly over the WNP region. The WNPRA is the summer-mean precipitation anomaly averaged over the WNP area (10N–20N, 120E–150E). The EASRA (EA Summer Rainfall Anomaly) is defined by using the summer-mean precipitation anomaly averaged over the EA area (30N–50N, 115E–150E) [*Lee et al.*, 2005], which is utilized as an index for the EA summer monsoon.

3. Results

[9] Precipitation anomalies over the WNP region (WNPRA) and WNPMI are highly correlated with each other (0.81) for the period 1979–2004. Here, we use both WNPMI and WNPRA to quantify the WNP summer monsoon. Figure 1 shows the time series of WNPMI, WNPRA, and EASRA together with the sliding correlation coefficients with an 11-year window. The marked differences between the period 1979–1993 and the period 1994–2004 are observed. EASRA is negatively correlated with WNPMI in the period 1994–2004, while the relationship is obscure in the period 1979–1993. We applied the statistical test suggested by *Gershunov et al.* [2001] to test whether the correlation difference between the two periods is significant or not. The correlation difference is significant at 90% confidence level according to the statistical test. The same is true of the relationship between WNPRA and EASRA. The correlation coefficients after 1994 are significant over 95% confidence level, when it is ascertained using Student's *t* test. We can assume that WNPMI, WNPRA, and EASRA are random signals because the auto-correlation of those time series is small. In addition, the correlation coefficients between EASRA and WNPMI are −0.38 and −0.82 for the periods 1979–1993 and 1994–2004, respectively. The linear relationship between the EA and the WNP summer monsoons is more evident in the recent decade (1994–2004) than in the previous decade (1979–1993). This observational evidence suggests that the relationship between the EA and the WNP summer monsoons exhibits a decadal change.

[10] Figure 2 shows the first two leading empirical orthogonal functions (EOF) and their corresponding principal components of summer-mean precipitation over the region, 10S–50N and 110E–180E. The variances of the first two leading modes account for 51% and 56% of the total variance for the period (1979–1993) and for the period (1994–2004), respectively. The left panels (Figures 2a and 2d) and the right panels (Figures 2b and 2e) are for the period 1979–1993 and for 1994–2004, respectively. The selection of the two periods is based on the sliding correlation analysis (Figure 1b). Figures 2c and 2f show the corresponding time series for the whole period 1979–2004. Note that the EOF 1 for 1979–1993 and the EOF 2 for 1994–2004 share some degree of similarity. These spatial patterns are commonly characterized by a large east-west contrast in the equatorial western Pacific between the eastern-central maritime continent and the equatorial western Pacific. This pattern is similar to that often seen during the developing phase of ENSO. Their principal components are indeed highly correlated Nino 3 SST index for both periods with the simultaneous correlation coefficient between the corresponding principal components and JJA-mean Nino3 index of 0.69. For simplicity, we refer to this mode as the ENSO mode. Results shown in Figures 2a, 2b, and 2c indicate that the ENSO-induced variability in the 1979–1993 period dominates and accounts for about 37% of the total variance, while it becomes less important (the second EOF) and accounts for 17% of the total variance for the period 1994–2004.

[11] Figures 2d and 2e show EOF 2 for the period 1979–1993 and the EOF 1 for 1994–2004, respectively. These two modes share very similar spatial structure, which is characterized by a maximum variability along the WNP summer monsoon trough titled from the Philippines to equatorial western Pacific with opposite polarity located

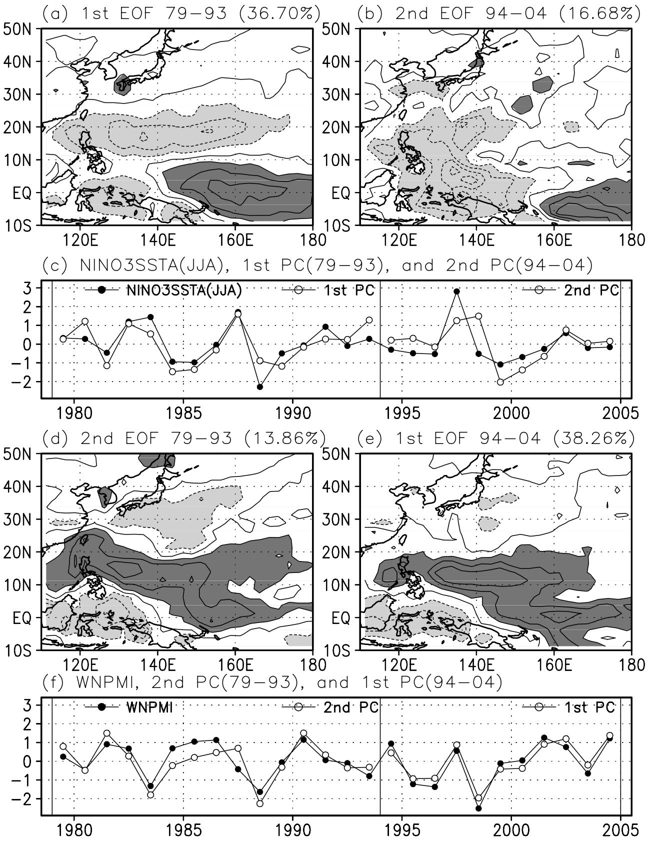


Figure 2. Eigenvectors of summer-mean (June, July, and August) precipitation over a specified region 110E–180, 10S–50N. (a) the first mode and (d) the second mode for the period 1979–1993, and (b) the second mode and (e) the first mode for the period 1994–2004. Contour interval is 0.03. Panel (c) shows the principal components of the EOF 1 for 1979–1993 and the EOF 2 for the 1994–2004 along with JJA (June, July, and August)-mean Nino3 index. Panel (f) shows the principal components of the EOF 2 for 1979–1993 and EOF 1 for 1994–2004 along with the WNPMI (WNP Monsoon Index). All principal components, the WNPMI, and the Nino3 index are normalized.

in the western-central Maritime Continent region. This pattern reflects the fluctuations of precipitation and associated latent heat forcing in the WNP monsoon trough and thus will be referred to as the WNP summer monsoon (WNPSM) mode. Their principal components are indeed highly correlated the WNP monsoon index with a correlation coefficient of 0.87, significant at 99% confidence level (Figure 2f). Results shown in Figures 2a, 2b, and 2c suggest that the WNPSM mode was of secondary importance in the 1979–1993 period, accounting for only 13% of the total variance; on the other hand, the WNPSM mode becomes dominant mode (the first EOF) and accounts for 38% of the total variance for the period 1994–2004.

[12] The results shown in Figure 2 suggest that the summer-mean precipitation over the WNP has two leading modes: an ENSO-related mode and a WNP summer monsoon mode. The dominant modes of precipitation anomalies in the WNP and EA region have a decadal change. The most dominant mode is associated with ENSO for the period (1979–1993) but is associated with the WNP summer monsoon for the period (1994–2004).

[13] Figure 3 shows map of simultaneous correlation between the JJA-mean geopotential height at 500 hPa and WNPMI for the periods 1979–1993 and 1994–2004, respectively. A pattern similar to the PJ (Pacific-Japan) pattern [*Nitta*, 1987] appears in 1979–1993 period. The two polarities of the PJ-like pattern are located in the Philippine Sea and Japan. The pattern resembles a barotropic Rossby-wave response to a subtropical forcing near the Philippines [*Nitta*, 1987; *Huang and Sun*, 1992]. An anomalous high (low) exists over Japan in a strong (weak) WNP summer monsoon year. The western edge of this anomalous geopotential height over Japan is confined to eastern Korea. Besides, the anomalous geopotential height associated with the WNP summer monsoon in the subtropics elongates to the dateline. The wave-like pattern during 1994–2004 that is shown in Figure 3b extends from southern China to Alaska via northern China, Korea, and northern Japan. The pattern has a vertically similar structure (figure not shown). This pattern is also similar to the circulation that is induced by convectional heating in the subtropics [*Wang et al.*, 2001]. The anomalous high (low) over northern China, Korea and Japan emerges in a strong (weak) WNP summer monsoon year. Moreover, the eastern edge of the pattern in the subtropics correlated with the WNP summer monsoon is confined to 150E. Also there are strong signals over northern Japan and Alaska. Southern China, northern China, northern Japan, and Alaska are located along a great circle of the earth. The above two different patterns indicate a decadal modulation in the relationship between the EA and the WNP summer monsoons. The pattern, which is shown in Figure 3b, is also significant by Monte-Carlo method. We took randomly 10,000 samples of 11 years and made probability distributions at each grid points. The pattern is significant at 99% confidence level using the sample distributions (figure not shown). In addition, it is suggested that the subtropical heating, which induces the midlatitude circulation, changes

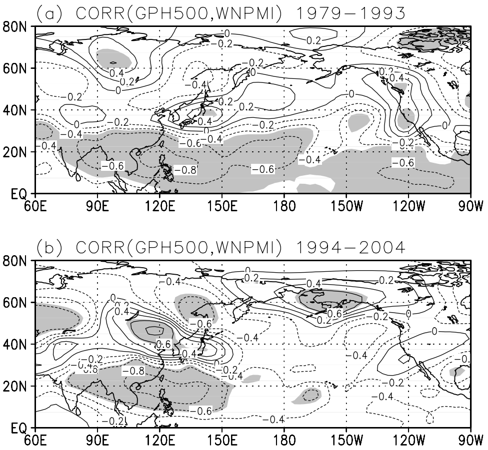


Figure 3. Map of correlation coefficients between JJA (June, July, and August)-mean geopotential height at 500 hPa and the WNPMI (WNP Monsoon Index) during the periods (a) 1979–1993, and (b) 1994–2004. Shaded areas indicate that the correlation is significant at 95% confidence level.

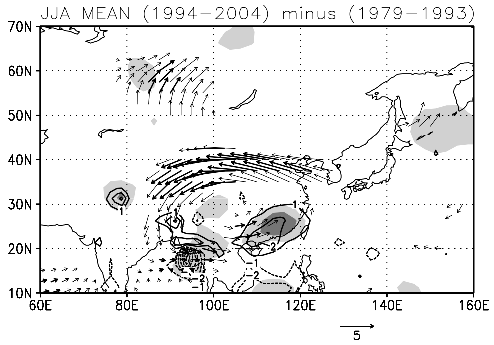


Figure 4. Differences in JJA (June, July, and August)-mean precipitation and JJA-mean 200 hPa horizontal winds between the periods 1979–1993 and 1994–2004. Light and dark shaded areas represent 95% and 99% confidence level by Lepage test, respectively. Thin and thick arrows are significant at 95% and 99% confidence level, respectively. Contour unit is mm/day and arrow unit is m/s.

on a decadal time scale. Meanwhile, a decadal change in the wind fields is also evident.

[14] Figure 4 shows changes in the JJA-mean precipitation and 200 hPa winds between the periods 1979–1993 and 1994–2004. Using the Lepage test, the mean change is marginally greater than the standard deviation of each variable at a 5% significance level. Distinctive changes in summer-mean 200 hPa zonal wind are found in northern China and precipitation in summertime over southeastern China has increased in the recent decades. This feature also appears consistent with outgoing longwave radiation, vertical p-velocity, and 200 hPa divergence (figure not shown). This means that east Asia has experienced a mean circulation change in summertime since the mid-1990s.

4. Discussion

[15] There are remarkable changes in JJA-mean upper level winds and summer-mean precipitation. These have been shown to be significant at 99% confidence level by the Lepage test. *Wang et al.* [2001] suggested that convective activity over the WNP was associated with the stationary wave-like pattern in the midlatitude. This pattern extends from east Asia to Alaska via northeastern China, Korea, and northern Japan. The different patterns shown in Figure 3 for the 1979–1993 and 1994–2004 periods are not unique to the period examined. The JJA-mean geopotential height patterns associated with WNPMI in the 1960s and the early 1970s are different from those in the 1980s and the early 1990s [see *Wu and Wang*, 2002, Figure 5]. Meanwhile, the 200 hPa zonal winds in summertime over northern China, where midlatitude jet is placed, significantly increased after the mid-1970s and decreased after the mid-1990s (figure not shown).

[16] The causes of the localized summer-mean precipitation anomaly over southeastern China in the mid-1990s and the JJA-mean wind variations on a decadal time scale in the recent decades have not been addressed in this paper. The summer-mean sea surface temperature in the western Pacific has an increasing trend in the recent decades (figure not shown). One possible reason is that an anomalous SST in the western Pacific, including the subtropics, produces the localized precipitation anomaly and the corresponding circulation anomaly. The roles of the western Pacific SST anomalies in the WNP and the EA summer monsoons are under investigation.

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