GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L21706, doi:10.1029/2007GL031977, 2007

Click Here for Full Article

Decadal change in east Asian summer monsoon circulation in the mid-1990s

MinHo Kwon,[1] Jong-Ghap Jhun,[2] and Kyung-Ja Ha[3]

Received 9 September 2007; accepted 9 October 2007; published 10 November 2007.

[1] A climate shift in the mid-1990s in summertime circulation over east Asia is described and the dynamics associated with the climate shift are discussed. The east Asian summer monsoon has a large interdecadal variability as well as interannual variability. It is suggested herein that the east Asian summer monsoon has undergone a decadal change in the mid-1990s. After the mid-1990s, there has been a significant decrease in the strength of zonal winds near the subtropical jet over the east Asia as well as a distinct increase in precipitation in the southeastern part of China. This decrease of the strength of zonal winds over east Asia could be understood as a barotropic response to a steady forcing associated with heating from increased precipitation. These decadal changes are significantly predominant only in the summertime. Concurrently, there has been a remarkable increase in the number of the typhoon passing through the southeastern part of China. It is suggested that the distinctive increase of the typhoon passing may be partly responsible for the increased precipitation in the same area after the mid-1990s. **Citation:** Kwon, M., J.-G. Jhun, and K.-J. Ha (2007), Decadal change in east Asian summer monsoon circulation in the mid-1990s, *Geophys. Res. Lett.*, *34*, L21706, doi:10.1029/2007GL031977.

1. Introduction

[2] The monsoon circulation has been recognized as an important system in the earth's hydrological cycle. East Asian summer monsoon (EASM) is a subsystem of Asia-Pacific summer monsoon in east Asia, which is the most populated area in the world. Therefore, the understanding of the EASM is one of the most imperative tasks in climate research. The EASM exhibits variability on various time-scales. In particular, the EASM has strong interannual variations of precipitation, which correlates strongly with eastern Pacific SST during the decaying phase of the ENSO [*Shen and Lau*, 1995; *Chang et al.*, 2000; *Wang et al.*, 2001; *Wu and Wang*, 2002]. In addition, the EASM has an interdecadal transition in the late-1970s, which is concurrent with the major climate shift in the tropical Pacific [*Hu*, 1997; *Wu and Wang*, 2002; *Chang et al.*, 2000; *Zhang et al.*, 2004]. In particular, EASM precipitation anomalies have a contrast of the South–North dipole structure in east Asia between the before and after periods of the late-1970s.

[1]Research Institute of Basic Sciences, Seoul National University, Seoul, South Korea.
[2]School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea.
[3]Division of Earth Environmental System, Pusan National University, Busan, South Korea.

Copyright 2007 by the American Geophysical Union.
0094-8276/07/2007GL031977$05.00

[3] Numerous previous studies have documented the decadal or interdecadal changes in east Asian summer monsoon around the late-1970s. However, decadal changes in east Asian summer monsoon in the mid-1990s have been hardly studied. Recently, *Kwon et al.* [2005] showed that there was a significant decadal change in relationship between east Asian and western North Pacific summer monsoons in the mid-1990s. They also showed that the ENSO-related mode for the EASM precipitation was significantly reduced during 1994–2004 compared to 1979–1993. Concurrently, the decade-averaged summer-mean circulation and precipitation show a big difference between the recent decade and the previous decade. Our study describes the abrupt change in mean fields over the EASM region around 1994 and investigates its potential causes.

[4] There are remarkable differences in summertime circulation between 1993 and 1994 in east Asia [e. g., *Park and Schubert*, 1997]. The periods of decadal variation could be easily separated because of the distinctive circulation difference of 1993 and 1994. This study analyzes decadal changes in summer circulation for the periods of 1979–1993 and 1994–2002 in east Asia.

2. Data and Methods

[5] The Climatic Research Unit (CRU) monthly precipitation data [*New et al.*, 2000], with spatial resolution of 0.5 by 0.5 degrees, were used for the period from 1979 to 2002. The European Centre for Medium Range Weather Forecasting (ECMWF) reanalysis data set [*Uppala et al.*, 2005] provides atmospheric data for the period 1958–2002. The variables used in this study include zonal and meridional winds at 200 hPa. The monthly means of these data have been entered into every grid with a horizontal resolution of 2.5 by 2.5 degrees. In addition, the western Pacific typhoon track data from the Joint Typhoon Warning Center (JTWC) were used for the period from 1945–2006 (https://metocph.nmci.navy.mil/jtwc/best_tracks/TC_bt_report.html).

[6] Since the number of sample is not large enough to determine the decadal change in the EASM, the study of the decadal change requires a more careful method to obtain information of statistical significance. In this study, 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 parent populations are unknown. *Hirakawa* [1974] demonstrated that the Lepage test is more statistically powerful than other non-parametric tests. 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

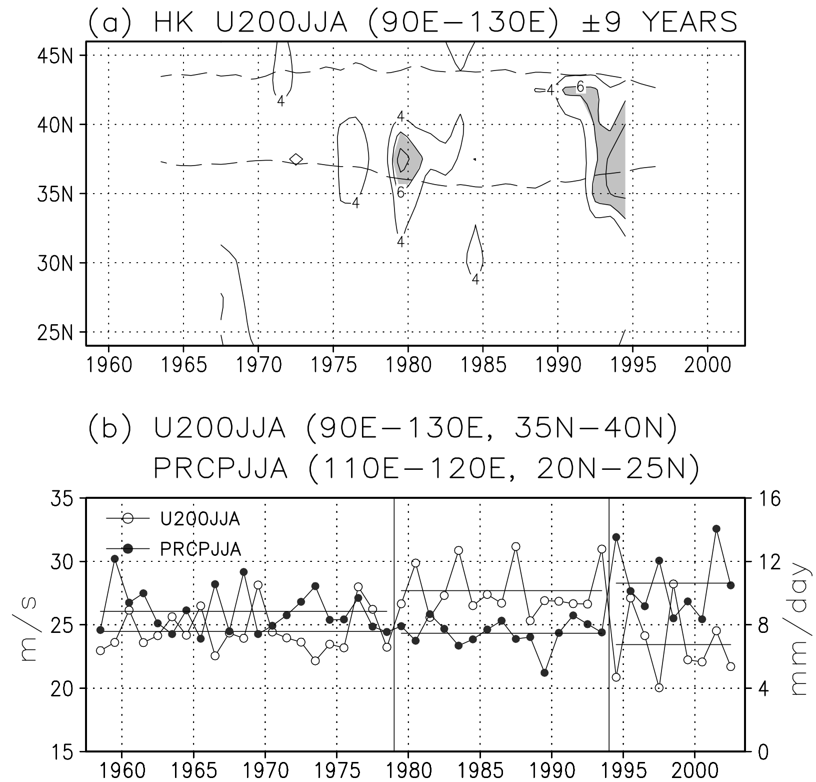

Figure 1. (a) Sliding Lepage statistics (HK) of JJA(June, July, and August)-mean zonal wind speed at 200 hPa, which are longitudinally averaged for 90E–130E before and after nine years from the ECMWF data set. Shaded areas indicate the exceeding of a significance level of 5% by the Lepage test. Horizontal dashed lines denote 11-year running mean of 25 m s^{-1} isotachs. (b) Time series of 200 hPa JJA-mean zonal wind speed for a region (90E–130E, 35N–40N) and JJA-mean precipitation (110E–120E, 20N–25N) from the CRU data set. Horizontal solid lines indicate averaged values for each decadal period. Units are m s^{-1} and mm day^{-1}, respectively.

change between two samples is significant at a confidence level of 95% or 99%, respectively.

[7] We used a barotropic model on the sphere to investigate the dynamical relationship between the subtropical heat source and its circulation response. The linearized barotropic vorticity equation is

$$\frac{\partial \zeta'}{\partial t} = -\overline{V} \cdot \nabla \zeta' - V'_{\psi} \cdot \nabla (f + \overline{\zeta}) - V'_{\chi} \cdot \nabla (f + \overline{\zeta}) - (f + \overline{\zeta}) \nabla \cdot V'_{\chi} - \kappa \zeta' - \varepsilon \nabla^4 \zeta'$$

where bar represents the zonal mean variables and prime is the deviation from the zonal mean state. V_{ψ} and V_{χ} are the rotational and divergent wind components, respectively. They are defined as follows:

$$V_{\psi} = \vec{k} \times \nabla \psi$$
$$V_{\chi} = \nabla \chi$$

where ψ and χ are stream function and velocity potential, respectively. The velocity potential and the zonal mean flow are held fixed as summertime climatological values obtained from the observational data set at the 500 hPa. The biharmonic diffusion coefficient is set to $\varepsilon = 10^{16}\, m^4\, s^{-1}$. The damping coefficient, $\kappa = 1.5 \times 10^{-6}\, s^{-1}$, is used in this model.

3. Results

[8] The Asian subtropical jet is normally located along the latitudinal band of 35N–45N in summertime. Figure 1a shows the Lepage statistics (HK) for summer-mean 200 hPa zonal wind speed, which are longitudinally averaged for 90E–130E. The Lepage statistic is known to be useful to detect an abrupt change between two periods. The large values of the Lepage statistic indicate the abrupt change around the year corresponding to the large value in Figure 1a. The area between these two 25 m s^{-1} isotachs in Figure 1a denotes the region exceeding 25 m s^{-1} of wind speed. It is noteworthy that the significant area for decadal changes locates between two 25 m s^{-1} isotach lines. The intensity of the subtropical jet has undergone two big changes in the late-1970s and in the mid-1990s. Time series of the JJA(June, July, and August)-averaged 200 hPa zonal wind for an area (90E–130E, 35N–40N) clearly shows two abrupt changes around 1979 and around 1994. In particular, the change in the 200 hPa zonal winds near the subtropical jet around 1994 is remarkable in east Asia. The abrupt change in the zonal wind speed of Asian subtropical jet region in the late-1970s is concurrent with the decadal change in east Asian monsoon circulation, which is associ-

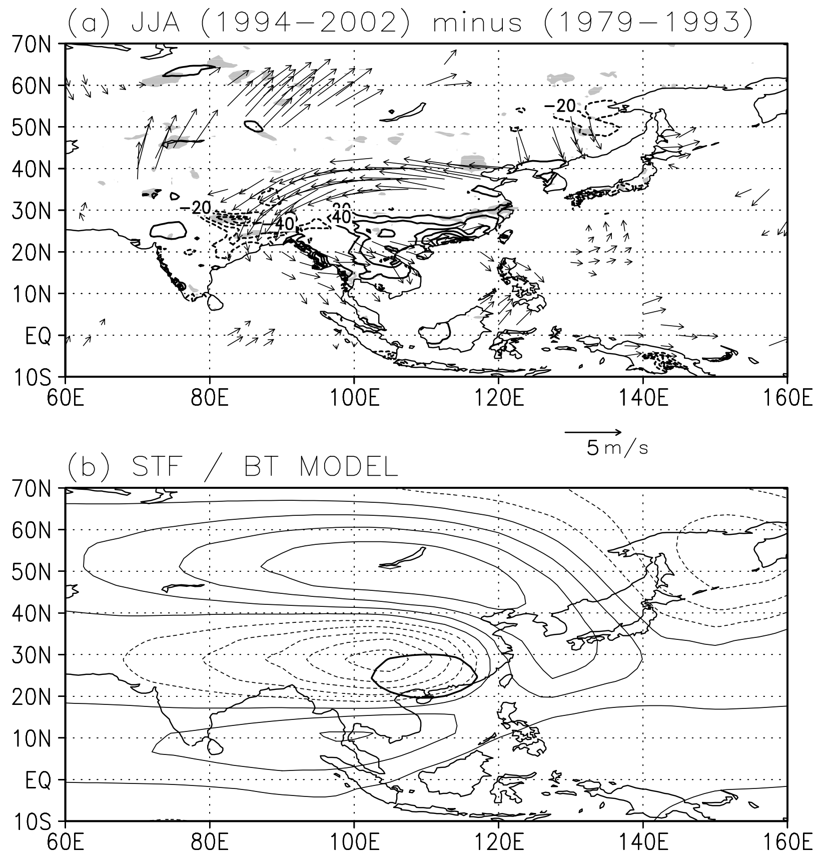

Figure 2. (a) Difference of JJA-mean precipitation (CRU) and difference of JJA-mean 200 hPa horizontal winds (ECMWF) between the periods 1979–1993 and 1994–2002. Shaded areas for precipitation represent a confidence level of 95% by the Lepage test. Plotted arrows are significant at 95% confidence level. Contour unit is mm month^{-1} and arrow unit is m s^{-1}. (b) Stream function anomalies as a barotropic response due to a steady divergence forcing over the region (100E–120E, 20N–30N) under 500 hPa climatological mean winds based on observations (ECMWF) during 1958–2002. Thick solid closed lines indicate divergence forcing. Contour interval is 1.0×10^5 m^2 s^{-1}. The maximum value of the half-period sinusoidal divergence forcing is 1.0×10^{-6} s^{-1}.

ated with changes in the mean state in the tropical Pacific. The significant change in upper-level zonal wind appears in both ECMWF (ERA40) and NCEP/NCAR reanalysis data sets, in which the obvious decadal change around 1994 occurs in the extended period to 2006. The decadal change in upper-level wind near the subtropical jet is associated with high pressure anomalies at all levels and the positive surface temperature anomaly in latitudinal range from 40N to 60N in east Asia (figures not shown). In addition, the abrupt change in precipitation over the southeastern part of China (110E–120E, 20N–25N) is obvious around 1994 (Figure 1b).

[9] Spatial patterns of the decadal change in the strength of the east Asian subtropical jet for summertime are displayed in Figure 2a. It is noteworthy that anomalous southwesterly wind in the west of Lake Baikal and anomalous northerly wind in the north of Korea as well as anomalous easterly wind in the west of the Asian jet region are found after the mid-1990s with the statistical significance of 5%. The similar changes in zonal wind at other levels are also significant. The analysis result from the NCEP/NCAR reanalysis data set as well as the ECMWF reanalysis data set indicates the same feature even though the analysis period extends to 2006. Figure 2a also shows an abrupt increase in summer-mean precipitation in the southeastern part of China after the mid-1990s. The monthly CRU data set [*New et al.*, 2000] was used for the precipitation analysis in Figure 2. The marked increase of summer precipitation in the southeastern part of China is also found in another precipitation data set, CPC Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1997; see *Kwon et al.*, 2005, Figure 4]. In addition, this feature also appears to be consistent with outgoing longwave radiation, vertical p-velocity, and 200 hPa divergence (figures not shown).

[10] The strength of the Asian subtropical jet has a tendency to be negatively correlated with precipitation amounts in the southeastern part of China in the summertime (Figure 1b). The correlation coefficient between two time series in Figure 1b is −0.58. The negative relationship is still valid even though the decadal variation is eliminated using a digital filter. The correlation coefficient between two time series, which are filtered for interannual time scale, is −0.42 for the period 1958–2002. This value is significant at 99% confidence level for the correlation coefficient between random time series. Here, the Lanczos band-pass filter [*Duchon*, 1979] is utilized to decompose the interannual component for the 2–7 year band. This negatively correlated relationship gives us the insight into the dynam-

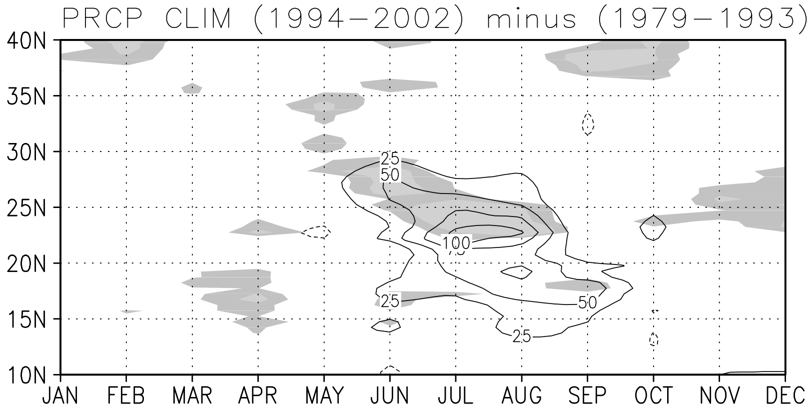

Figure 3. Difference of climatology for the periods 1979–1993 and 1994–2002 in summer-mean precipitation averaged over 100E–120E from the CRU monthly data set. Shaded areas are significant at a confidence level of 95% by the Lepage test. Unit is mm month^{-1}.

ical connection between the strength of the east Asian subtropical jet and precipitation amounts in the southeastern part of China in summer.

[11] Accordingly, decadal variations in the dynamic variable of zonal wind and the thermodynamic variable of precipitation amount seem to be dynamically linked for the summertime in east Asia. As a matter of fact, such a circulation change could be understood as a barotropic response of a steady forcing. We used a barotropic model to impose a divergence forcing in the region, where summertime precipitation has been increased in the recent decade (1994–2002). The two-dimensional sinusoidal forcing of divergence in the region (100E–120E, 20N–30N) with the bell shape of x and y directions, elsewhere divergence values are zero, has been prescribed in the barotropic model. The barotropic stream function response to the steady forcing resembles the decadal change in observed circulation after the mid-1990s (Figure 2b). The resemblance of wind differences is found not only near the subtropical jet but also west of Lake Baikal and north of Korea. These results imply that an anomalous heating due to the increased precipitation in the southeastern part of China could give rise to a significant decrease of the Asian subtropical jet strength. Furthermore, the coupled change of wind and precipitation in east Asia is not confined to the recent two decades. There was another big circulation change in the late-1970s (Figure 1b). Observation data exhibit precipitation change corresponding to this latter circulation change at that time. This decadal transition of summer precipitation in the southern part of east China is associated with the climate shift in the late-1970s. *Hu* [1997] showed that the precipitation change in the late-1970s was characterized by the intensification and southwestward extension of the western Pacific subtropical high (WPSH). *Zhang et al.* [2004] investigated the decadal change in the spring snow depth over the Tibetan Plateau and its impact on the EASM using station observation data of snow depth before and after the late-1970s. On the other hand, the precipitation change in the mid-1990s is not correlated with the extension of the western boundary of the western Pacific subtropical High and has no relation with snow contents over Tibetan Plateau on decadal time scale (figure not shown).

[12] The decadal changes in precipitation and circulation in east Asia in the mid-1990s are distinctive only in the summer. Figure 3 shows the difference of summer-mean precipitation climatology for two epochs, 1979–1993 and 1994–2002. The largest climatological differences in precipitation are dominant in June, July, and August in the southeastern part of China. In particular, the differences in 20N–30N are statistically significant. The maximum difference of the monthly precipitation is about 100 mm. The differences in the lower latitudes (15N–20N) are not significant even though the differences are large values of 50–70 mm per month. It seems to be due to the large interannual variability of the precipitation in the low-latitude region. This fact provides us the insight that the localized precipitation anomaly is associated with active meteorological phenomena only in the summer.

[13] The typhoon activity in the western Pacific is a candidate for the cause of the summer precipitation increase over the southeastern part of China after the mid-1990s. The summertime typhoon passage frequency per year passing through each grid box (2.5 by 2.5 degrees) is remarkably increased in the western North Pacific after the mid-1990s (Figure 4). In particular, the maximum values of the typhoon frequency in the vicinity of the Philippines are about 1.2 and 2.8 per grid box in 1979–1993 and in 1994–2002, respectively. Figure 4 also shows typhoon tracks passing through the southeastern part of China. The numbers of summertime typhoon passing through the southeastern China during the same number of years (i.e., 9 years for both periods) before and after 1994 are 23 and 31, respectively. This distinct increase in typhoon activity for the recent period is one of evidences for a significant climate shift in the mid-1990s even though the increase of the typhoon activity might by partially responsible for the increased precipitation in the southeastern part of China.

4. Summary and Discussion

[14] There were remarkable circulation changes over the east Asian region around 1994 in the boreal summertime. In particular, there has been a significant decrease in the strength of upper-level winds near the subtropical jet over the east Asia after the mid-1990s. Also, a distinctive

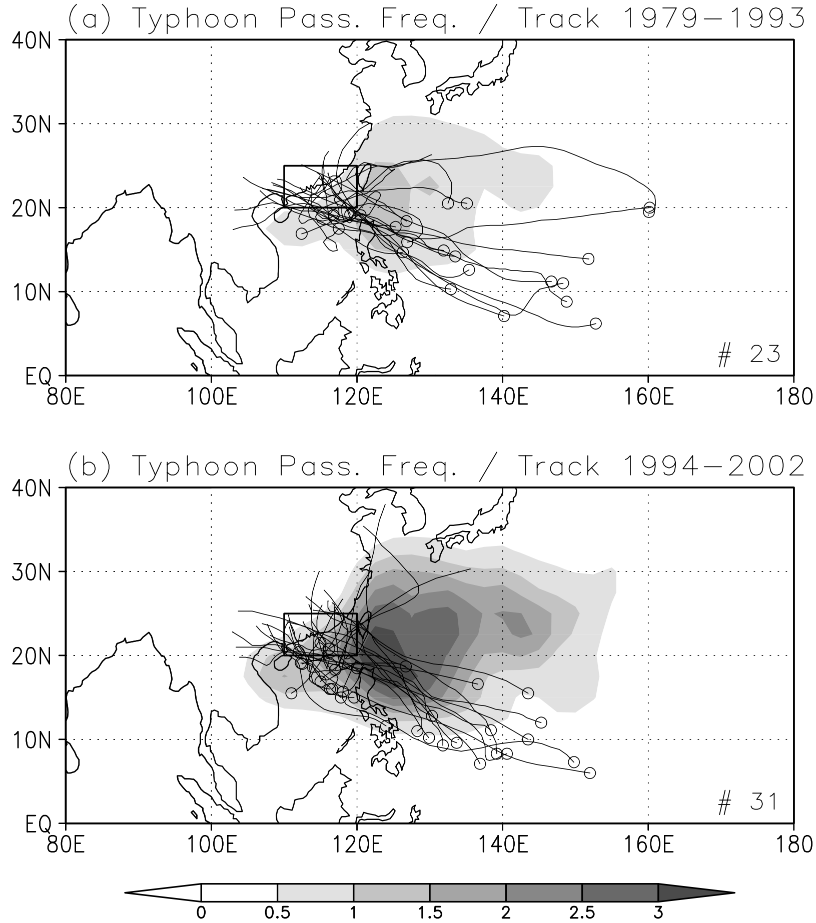

Figure 4. (a) Typhoon passage frequency per year passing through each grid points of 2.5 by 2.5 degrees for the period 1979–1993 and typhoon tracks passing through southeastern part of China (boxed area) for the period 1985–1993. Open circles indicate the generation position of the each typhoon. (b) Same as Figure 4a but for the period 1994–2002.

increase in precipitation in the southeastern part of China has been observed after the mid-1990s. These abrupt changes appear consistently in different data sets of variables. The mean circulation change after the mid-1990s, especially near the subtropical jet over the east Asia, has a barotropic structure. The decadal change in summer-mean precipitation over the southeastern part of China derives the anomalous upper-level divergence, which appears significantly. We used a barotropic model with the divergence forcing in order to confirm observation results. It is found from the model result that the steady divergence at upper level balances the mid-latitude circulation under the mean wind. This balance seems to be associated with an apparent decrease in the strength of the Asian subtropical jet and a remarkable increase of precipitation in the southeastern part of China.

[15] The abrupt increase of precipitation in the southeastern part of China after the mid-1990s is obvious only in the summertime. The changes in the typhoon activity could be a cause of the precipitation increase in the southeastern part of China in the recent period (1994–2002). The brisk activity of typhoon in the recent decade could be related to the increasing trend of SST in the western Pacific, which could give rise to vigorous evaporation in the same area.

[16] **Acknowledgment.** This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-4205.

References

Chang, C. P., Y. Zhang, and T. Li (2000), Interannual and interdecadal variations of the east Asian summer monsoon and the tropical SSTs. Part I: Roles of the subtropical ridge, *J. Clim.*, *13*, 4310–4325.

Duchon, C. E. (1979), Lanczos filtering in one and two dimensions, *J. Appl. Meteorol.*, *18*, 1016–1022.

Hirakawa, K. (1974), The comparison of powers of distribution-free sample test, *TRU Math.*, *10*, 137–161.

Hu, Z. Z. (1997), Interdecadal variability of summer climate over east Asia and its association with 500 hPa height and global sea surface temperature, *J. Geophys. Res.*, *102*, 19,403–19,412.

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.

Lepage, Y. (1971), A combination of Wilcoxson's and Ansari-Bradley's statistics, *Biometrika*, *58*, 213–217.

New, M., M. Hulme, and P. Jones (2000), Representing twentieth-century space-time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate, *J. Clim.*, *13*, 2217–2238.

Park, C.-K., and S. D. Schubert (1997), On the nature of the 1994 east Asian summer drought, *J. Clim.*, *10*, 1056–1070.

Shen, S., and K. M. Lau (1995), Biennial oscillation associated with the east Asian monsoon and tropical sea surface temperatures, *J. Meteorol. Soc. Jpn.*, *73*, 105–124.

Uppala, S. M., et al. (2005), The ERA-40 reanalysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–3012.

Wang, B., R. Wu, and K.-M. Lau (2001), Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific–east Asian monsoons, *J. Clim.*, *14*, 4073–4090.

Wu, R., and B. Wang (2002), A contrast of the east Asian summer monsoon–ENSO relationship between 1962–77 and 1978–93, *J. Clim.*, *15*, 3266–3279.

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

Yonetani, T., and G. J. McCabe (1994), Abrupt changes in regional temperature in the conterminous United States, *Clim. Res.*, *4*, 12–23.

Zhang, Y., T. Li, and B. Wang (2004), Decadal change of the spring snow depth over the Tibetan Plateau: The associated circulation and influence on the east Asian summer monsoon, *J. Clim.*, *17*, 2780–2793.

K.-J. Ha, Division of Earth Environmental System, Pusan National University, Busan 609-735, South Korea.

J.-G. Jhun, School of Earth and Environmental Sciences, Seoul National University, Seoul 151-747, South Korea. (jgjhun@snu.ac.kr)

M. Kwon, Research Institute of Basic Sciences, Seoul National University, Seoul 151–747, South Korea.