GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L15803, doi:10.1029/2006GL026418, 2006

Trends in Seoul (1778–2004) summer precipitation

Bin Wang,[1,2] Qinghua Ding,[1] and Jong-Ghap Jhun[3]

Received 26 March 2006; revised 21 May 2006; accepted 28 June 2006; published 4 August 2006.

[1] Precipitation data for Seoul, Korea, have been recorded since 1778, representing one of the world's longest instrumental measurements of daily precipitation. Trends in summer precipitation amount, intensity, and indices of climate extremes are studied. The detected trends were tested using trend-to-noise ratio test, nonparametric Mann–Kendall rank statistic and Monte Carlo simulation procedure. Over the past 227 years and in the twentieth century, the June–September total precipitation amount has a trend significant at 95% confidence level; the numbers of torrential rainy days with precipitation greater than 75 mm, the highest one-day rainfall amount, the number of extremely wet days defined as the 99 percentile of the distribution of daily precipitation, and the precipitation amount falling in the extremely wet days, all have a trend significant at 99% confidence level. An intensity index that captures the combined effects of precipitation frequency and intensity, calculated as the number of heaviest rainy days that constitute 67% of the total precipitation shows a decreasing trend significant at 99% confidence level, suggesting an increase in precipitation intensity. However, the trends calculated for the pre-1950 period (1778–1949) are all insignificant except the intensity index, suggesting that real trends occur only in the recent 55 years. Nevertheless, the pronounced recent increasing trends since 1950 are unprecedented. What give rise this trend remain elusive. **Citation:** Wang, B., Q. Ding, and J.-G. Jhun (2006), Trends in Seoul (1778–2004) summer precipitation, *Geophys. Res. Lett.*, *33*, L15803, doi:10.1029/2006GL026418.

1. Introduction

[2] Understanding the changes in the East Asian (EA) monsoon rainfall in a warming environment has been both a scientific challenge and of societal importance. Careful study of past changes may provide useful clues for understanding the effects of global warming on the monsoon precipitation, especially extreme events.

[3] Seoul (37°34′N, 126°58′E), Korea, is an excellent site for study because it is located at the geographic center of the EA monsoon region (20°–50°N, 100°–145°E) and because it has one of the world's longest records of instrumental measurements of daily precipitation since 1771. Before 1908, the rainfall was measured using *Chuk-woo-kee*, a rain-measuring device that is essentially the same as the modern rain gauge [*Wada*, 1910; *Hahn*, 1996]. *Wada* [1917] first calibrated the *Chuk-woo-kee* data and compiled a monthly-mean precipitation data set, which has subsequently been used to investigate interannual variability [*Jung and Lim*, 1994]. Recent *Chuk-woo-kee* data set re-compiled by *Lim et al.* [1996] has been recognized more reliable and complete than Wada's [*Jhun and Moon*, 1997; *Park and Yadav*, 1998]. Based on this monthly rainfall data, *Ha and Ha* [2006] found two significant changing points for April–November rainfall occurring around 1881 and 1952.

[4] The *Chuk-woo-kee* data used in this study were originally compiled from two sets of royal diaries from the *Chosun* Dynasty, "Seungjungwonilgee" (the national treasure No. 303 of South Korea) and "Ilsungrok" (the national treasure No. 153 of South Korea), which are kept in Kyujangkag, a special library at Seoul National University. These official documents recorded the dates of each rainy event, along with its starting and ending hours and the total amount of rainfall, as well as a description of rainfall intensity and cloud conditions. The dates and times of rainfall originally recorded by using the lunar calendar were converted into local times and dates of the corresponding solar calendar. The ancient units used to measure the rainfall were also converted to millimeters. No decimals were recorded in the ancient record; thus, rain events of less than about 2 millimeter were neglected.

[5] *Jhun and Moon* [1997] further reconstructed *daily* rainfall data set for the period of 1778–1907. Data for the beginning years from 1771 to 1777 were excluded because the diary is partially missing; another period with missing daily data is the Korean War (1950–53). The daily data were compiled from a proxy hourly data which was produced by uniformly distributing the total rainfall amount of each event across each hour of the event. The diurnal cycle derived from the *Chuk-woo-Kee* hourly data set agrees very well with the diurnal cycle derived from the modern rain-gauge observation [*Jung et al.*, 2001], which lends support for the reliability of the proxy hourly data and the daily data. For current study, a complete Seoul daily rainfall data set consisting of *Chuk-woo-kee* timeframe (1778–1907) and the modern observation period (1908–2004) [*Jung et al.*, 2001] is constructed. The standard deviations of the monthly and seasonal rainfall derived from the two periods are comparable. As far as extreme events are concerned, the differences between *Chuk-woo-kee* and modern instrumental measurements are not expected to have appreciable effects on our analysis results.

[6] Three methods were used to test the significance of the derived trend. The first is trend-to-noise ratio test which relies on least square (LS test hereafter) regression model [*Woodward and Gray*, 1993]. The second method to quantify the direction and magnitude of the trend of raw data is based on the nonparametric Mann–Kendall (MK test here-

[1]Department of Meteorology, University of Hawaii at Manoa, Honolulu, Hawaii, USA.
[2]Also at International Pacific Research Center, University of Hawaii at Manoa, Honolulu, Hawaii, USA.
[3]School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea.

0094-8276/06/2006GL026418$05.00

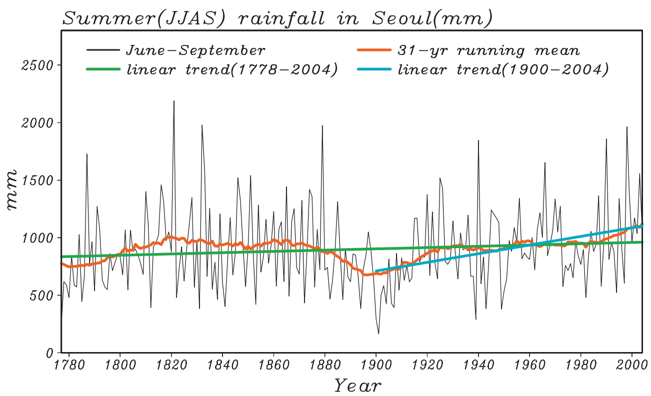

Figure 1. Time series of summer (June–September) precipitation in Seoul from 1778 to 2004. The red line denotes 31-year running mean. The green line represents a linear trend for 1778–2004, and the blue line shows the trend for 1900–2004; both were obtained by least-square regression. The seasonal mean data is constructed from monthly data, so there is no missing during 1950–1953.

after) rank statistic [*Kendall*, 1955]. Unlike the linear regression method, this test is insensitive to individual outliers and to the start and end points. Alternatively, the significance of trend is retested through 1000-ensemble Monte Carlo (MC test hereafter) simulation procedure as explained in *Wilks* [1995]. We also take into account the effect of autocorrelation when assessing trends and their significance level [*Chen*, 1982].

2. Total Amount of Summer Precipitation

[7] The summer precipitation in Seoul exhibits remarkable natural fluctuations. Figure 1 shows that the mean summer precipitation (from June to September, JJAS hereafter) in Seoul from 1778–2004 is 901 mm, with a standard deviation of 344 mm. The maximum JJAS rainfall is 2,190 mm in 1821, which is more than 13 times that of the driest summer rainfall of 164 mm in 1901. Both the extreme years occurred more than 100 years ago, suggesting a remarkably large natural rainfall variability.

[8] Climatological condition is often determined by a 30-year average condition [*Guttman*, 1989], which gives a reasonable estimation of the weather statistics that define climate conditions. We note that the 30-year averaged JJAS precipitation between the driest 30-year period (1885–1914) and the wettest 30-year period (1975–2004) differs by 315 mm, indicating considerable long-term changes in summer rainfall climatology. These two extreme 30-year means occurred, respectively in the beginning and the end of the 20th century, yielding a remarkable trend for the last century (Figure 1). Whether it arises from natural variations or anthropogenic changes deserve cautiously further investigation.

[9] Regardless of the large amplitude of year-to-year variations, the total summer rainfall has increased by approximately 7% per century, or a total of 15% in the past 227 years. Using three methods, this linear increasing trend, obtained by least-square regression, is significantly different from zero at the 95% confidence level (See Table 1). The increasing trend is particularly notable in the 20th century, increasing from 711 mm in 1900 to 1,097 mm in 2004, a growth of about 54% during the century. The trend shown in Figure 1 is consistent with the recent 100-year trend seen in the lower reach of the Yellow River and Korean peninsula, documented in the previous studies devoted to the trend analysis of global land precipitation [*Dai et al.*, 1997; *Intergovernmental Panel on Climate Change*, 2001; *Chen et al.*, 2002]. A closer inspection of monthly precipitation reveals that the JJAS trend is primarily associated with the increasing trend during July and August (figure not shown).

[10] We should, however, be cautious about the increasing trends seen in Figure 1. The trend over the past 227 years, especially over the last 100 years, is most likely exaggerated by the fluctuations occurring on a centennial time scale. There were two mega-drought periods (1778–1800 and 1875–1908) and two mega-flooding periods (1800–1840 and 1980–2004) in the Seoul record. Both trends in the last centaury and over the entire 227-year period were computed starting from one of the mega-drought periods. If the calculation of trend starts from 1820, no significant trend is detected. Furthermore, the precipitation record before 1950 does not have significant trend either. A real trend has occurred only in the last 55 years.

3. Precipitation Intensity

[11] The precipitation intensity, however, exhibits more reliable evidence of an increasing trend over the past 227 years. Two parameters were used to quantify the precipitation intensity. One is an intensity index that captures the combined effects of precipitation frequency and intensity on a water supply, which is defined by the number of heaviest rainy days that constitute 67% of the total precipitation [*Sun et al.*, 2006]. Smaller values of this index mean stronger intensity. Figure 2 shows that the intensity index has decreased from 10.5 in 1778 to 9.8 in 2004, about a 7% decrease across the entire period, implying that the majority of the summer rainfall occurred in a fewer number of days. The statistical significance of this trend is presented in Table 1. The intensity index trend is less affected by centennial scale variability compared to the JJAS total precipitation. The other criteria used to define the intensity index (for instance 50%, 60%, 80%) were tested. The results show that the aforementioned conclusion is not sensitive to choice of the given criterion.

Table 1. Trends (Per Century) and Their Levels of Statistical Significance (%) Determined Using Least Square (LS), Mann-Kendal (MK), and Monte Calos (MC) Methods

Quantities Examined	Trends[b]	LS	MK	MC	Figure
JJAS rainfall	7%	95	95	95	Figure 1
Intensity index	3%	95	99	99	Figure 2
Mean rainfall of rainy day	7%	99	99	99	Figure 3
Heavy rainy days (≥75 mm)	17%	99	99	99	Figure 4
Heavy rainy days (≥200 mm)	133%	99	N/A[a]	99	Figure 4
Highest 1-day rainfall	14%	99	99	99	Figure 5
Extremely wet day	68%	99	N/A[a]	99	Figure 5
Rainfall of extremely wet day	75%	99	N/A[a]	99	Figure 5

[a]MK test are not applicable when a large number of ties impede the unequivocal assignment of ranks, especially when the trend of rare events are considered (marked as N/A).

[b]Trend is obtained based on the regressed curve.

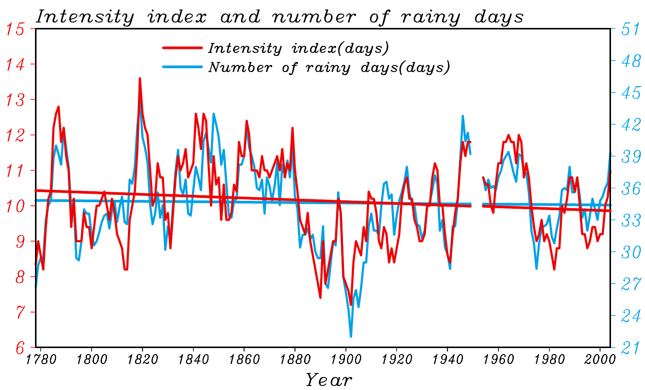

Figure 2. Running five-year means for the intensity index for Seoul's precipitation (red). The intensity index is defined by the numbers of heaviest rainy days in which 67% of the total precipitation falls in a given summer. Also shown is the number of rainy days with daily precipitation exceeding 2 mm (blue). The trends are obtained by least-square regression.

Of particular note is that the trend in intensity index is significant at 95% confidence level even for the pre-1950 period. If the criterion for intensity index increases to 100%, the intensity index is nearly equivalent to the number of "rainy day" of the whole summer season. Because the rain events of less than about 2 millimeter were neglected during *Chuk-woo-kee* period, the "rainy day" here means that daily precipitation exceeds 2 mm. The number of "rainy day" has no significant trend (Figure 2). Thus, the significant decreasing trend of intensity index (Figure 2) suggests the inconspicuous strengthening of the intensity of extreme events.

[12] The second parameter measuring intensity is the mean rainfall of each "rainy day". The trend of the time series of mean rainfall of each rainy day for each summer was computed by using least-square regression (Figure 3). The obtained trend is statistically significant at the 99% confidence level (Table 1). Taken together, the results depicted in Figures 2 and 3 show an increase in the overall precipitation intensity.

4. Extreme Events

[13] Four indices of precipitation extremes have been selected in reference to the indices of surface data recommended by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) [*Peterson*, 2005]. The first index is the number of torrential rainy days (defined as days with precipitation greater or equal to 75 mm) during JJAS. The 5-year running mean shows an increase trend which is obtained using logistic regression, the most commonly-used statistical method to assess the climatological trends in the frequency of extreme precipitation events based on the stochastic concept of binomial distributed counts [*Frei and Schär*, 2001]. The number of torrential rainy days has increased by about 17% per century and 38% for the entire 227-year period, which is statistically significant at the 99% confidence level, using the null-hypothesis of zero increase (Table 1). The increasing numbers of torrential rainy days are robust because similar trends are also seen in the numbers of days with daily rainfall exceeding 50 mm and 100 mm (not shown), and 200 mm (Figure 4).

[14] Figure 5 shows time series of (a) summer highest 1-calendar day precipitation amount, (b) the number of extremely wet days and (c) the precipitation amount falling in the extremely wet days. Here the extremely wet days are defined as the 99 percentile of the distribution of the summer daily precipitation amount in the 227-year period. The ratio between the precipitation falling in extremely wet days and the total precipitation shows a similar result (figure not shown). The trends of the highest 1-day precipitation amount is significant at 99% confidence level; the trends calculated for the number of days and total precipitation of the extremely wet days are significant at 99% confidence level (Table 1). Together, Figures 4 and 5 suggest a significant increasing trend of extremely heavy precipitation events.

5. Remarks and Discussion

[15] Significant and consistent increasing trends in the precipitation amount, intensity, and extremely wet events

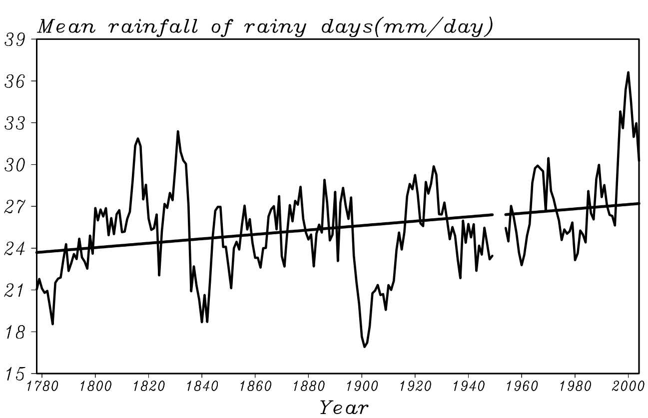

Figure 3. Running five-year means for the mean rainfall of JJAS rainy days. The rainy day is defined by daily precipitation exceeding 2 mm. The trends are obtained by least-square regression.

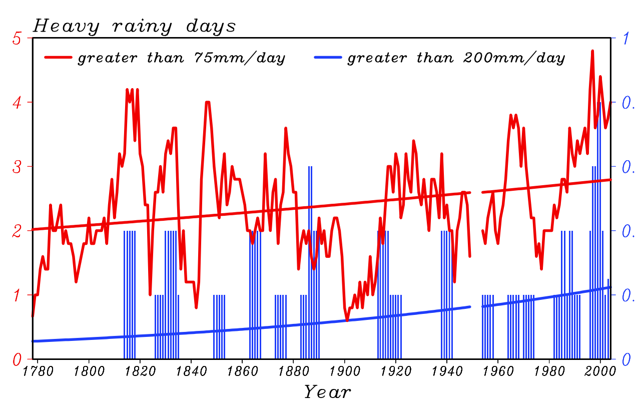

Figure 4. Running five-year means of the number of days per year with daily precipitation greater or equal 75 mm (red) and 200 mm (blue), respectively. Also shown are the corresponding trends obtained by logistic regression.

are detected for the 227-year record at Seoul (Table 1). These trends are particularly pronounced in the twentieth century (Figures 1 through 5). We note, however, all these long-term trends are primarily due to the remarkable increases in the second half of the twentieth century, especially due to the highest 30-year mean precipitation occurred in the last 30 years. Furthermore, the trends for the past 227 years and for the twentieth century are partially attributed to the abrupt change in the recent 50 years and the mega-drought periods which occurred in the beginning of the 227-year record and in the beginning of the twentieth century. Of also note is that the time series shown in Figures 1–5, in general, do not show significant trends for the period before 1950s except the intensity index. The summer precipitation in Seoul has remarkable fluctuations ranging from 164 mm in 1901 to 2,190 mm in 1821 (Figure 1). These historical extremes suggest that the natural variability itself is huge.

[16] Nevertheless, the increasing trends since 1950s are robust and unprecedented. A question arises as to whether the recent increasing trends in Seoul precipitation are a local feature or they reflect large scale changes in the East Asian summer monsoon. The epochal changes of JJAS rainfall between the two epochs prior to and after 1976 (post-76 minus pre-76 epoch) shows that the summer monsoon precipitation has increased in a southwest-northeast oriented belt from the middle-to-lower Yangtze River Valley across East China Sea and South Korea to northern Japan; meanwhile the rainfall has decreased to the north and south of the enhanced Meiyu/Baiu rain belt (Figure 6). This "sandwich" feature indicates that the well recognized "Southern China flood and northern China drought" trend in the last 50 years [e.g., *Nitta and Hu*, 1996; *Gong and Ho*, 2002; *Yu et al.*, 2004; *Wang and Ding*, 2006] is a part of the large-scale changes in East Asian monsoon. It suggests that the Meiyu/Baiu/Changma have been enhanced in the recent 28 years, especially over the Korea peninsula, which corroborates the finding shown in Figure 1. Thus, the increasing trend during the last 56 years detected from Seoul data reflect large scale changes in the East Asia monsoon region. Identifying the causes of the increasing rainfall remains elusive and calls for further investigation.

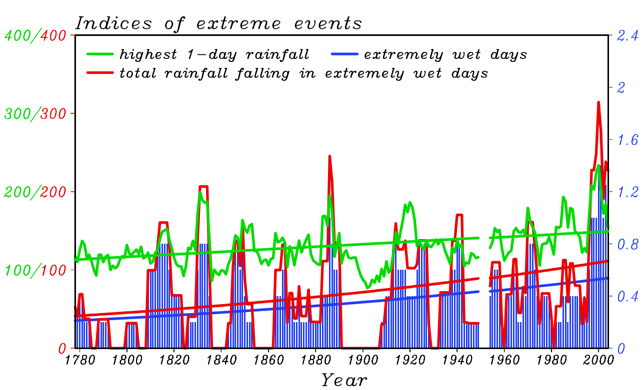

Figure 5. Running five-year means of the summer highest 1-calendar day precipitation amount (green), the number of extremely wet days (blue) and the precipitation amount falling in the extremely wet days (red). The extremely wet days are calculated as the 99th percentile of the distribution of the summer daily precipitation amount in the 227-year period. The scale of the green and red curve is shown in left y-axis. Also shown are the corresponding trends obtained by least-square regression for the green curve and logistic regression for the blue and red curve.

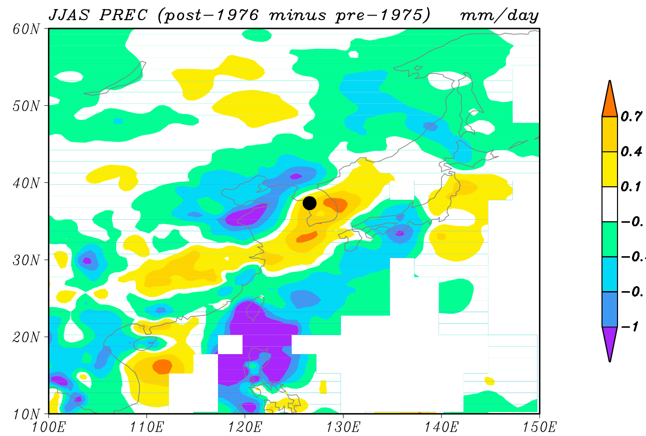

Figure 6. Epochal changes in JJAS rainfall (post-76 minus pre-76 epoch). The data used here were obtained from PREC/L data for the period of 1948–2003 [*Chen et al.*, 2002]. Seoul is marked as the solid black circle.

[17] **Acknowledgment.** This research is supported in part by NOAA and the International Pacific Research Center, the Ministry of Environment of Korea under "The Eco-technopia 21 project", and the Korea Meteorological Administration under "Meteorological and Earthquake R & D programs".

References

Chen, M., P. Xie, J. E. Janowiak, and P. A. Arkin (2002), Global land precipitation: A 50-yr monthly analysis based on gauge observations, *J. Hydrometeorol.*, *3*, 249–266.
Chen, W.-Y. (1982), Fluctuations in Northern Hemisphere 700 mb height field associated with southern oscillation, *Mon. Weather Rev.*, *110*, 808–832.
Dai, A., I. Y. Fung, and A. D. D. Genio (1997), Surface observed global land precipitation variations during 1900–88, *J. Clim.*, *10*, 2943–2962.
Frei, C., and C. Schär (2001), Detection probability of trends in rare events: Theory and application to heavy precipitation in the Alpine region, *J. Clim.*, *14*, 1568–1584.
Gong, D., and C. Ho (2002), Shift in the summer rainfall over the Yangtze River valley in the late 1970s, *Geophys. Res. Lett.*, *29*(10), 1436, doi:10.1029/2001GL014523.
Guttman, N. B. (1989), Statistical descriptors of climate, *Bull. Am. Meteorol. Soc.*, *70*, 602–607.
Ha, K.-J., and E. Ha (2006), Climatic change and interannual fluctuations in the long-term record of monthly precipitation for Seoul, *Int. J. Climatol.*, *26*, 607–618.
Hahn, S. D. (1996), *Invention of the Rain Gauge and its National Operations* (in Korean), 374 pp., Hahnguk Acad. Hydrogr. Nature, Busan, South Korea.
Intergovernmental Panel on Climate Change (2001), Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.
Jhun, J.-G., and B.-K. Moon (1997), Restorations and analyses of rainfall amount observed by Chukwookee (in Korean), *J. Korean Meteorol. Soc.*, *33*, 691–707.
Jung, H.-S., and G.-H. Lim (1994), On the monthly precipitation amounts and number of precipitation days in Seoul (in Korean), 1770–1907, *J. Korean Meteorol. Soc.*, *30*, 487–505.
Jung, H.-S., G.-H. Lim, and J.-H. Oh (2001), Interpretation of the transient variations in the time series of precipitation amounts in Seoul, Korea. part I: Diurnal variation, *J. Clim.*, *14*, 2989–3004.

Kendall, M. G. (1955), *Rank Correlation Methods*, 2nd ed., 196 pp., Oxford Univ. Press, New York.

Lim, G.-H., J.-G. Jhun, and J.-H. Oh (1996), Assessment of climatological precipitation amount in the Korean peninsula in terms of the precipitation records of Korean rain gauge and precipitation model output (in Korean), *Rep. KOSEF 93-0700-06-02-3*, 165 pp., Seoul Natl. Univ., Seoul, South Korea.

Nitta, T., and Z.-Z. Hu (1996), Summer climate variability in China and its association with 500 hPa height and tropical convection, *J. Meteorol. Soc. Jpn.*, *74*, 425–445.

Park, W.-K., and R. R. Yadav (1998), Reconstruction of May precipitation (A. D. 1731–1995) in west-central Korea from tree rings of Korean red pine (in Korean), *J. Korean Meteorol. Soc.*, *34*, 459–465.

Peterson, T. C. (2005), Climate change indices, *World Meteorol. Organ. Bull.*, *54*, 83–86.

Sun, Y., S. Solomon, A.-G. Dai, and R. W. Portmann (2006), How often does it rain?, *J. Clim.*, *19*, 916–934.

Wada, Y. (1910), Academic report from Korea observation stations (in Japanese), report, 108 pp., Inchon Weather Service, Inchon, South Korea.

Wada, Y. (1917), Reports on the survey of the ancient records of rainfall observation in Korea (in Japanese), 200 pp., Ilhan Print Cooperation, Seoul, South Korea.

Wang, B., and Q. Ding (2006), Changes in global monsoon precipitation over the past 56 years, *Geophys. Res. Lett.*, *33*, L06711, doi:10.1029/2005GL025347.

Wilks, D. S. (1995), *Statistical Methods in the Atmospheric Sciences: An Introduction*, 467 pp., Elsevier, New York.

Woodward, W. A., and H. L. Gray (1993), Global warming and the problem of testing for trend in time series data, *J. Clim.*, *6*, 953–962.

Yu, R., B. Wang, and T. Zhou (2004), Tropospheric cooling and summer monsoon weakening trend over East Asia, *Geophys. Res. Lett.*, *31*, L22212, doi:10.1029/2004GL021270.

Q. Ding and B. Wang, Department of Meteorology, University of Hawaii at Manoa, 2525 Correa Road, HIG 350, Honolulu, HI 96822, USA. (wangbin@hawaii.edu)

J.-G. Jhun, School of Earth and Environmental Sciences, Seoul National University, Seoul 151-742, South Korea.