Variability and Singularity of Seoul, South Korea, Rainy Season (1778–2004)

BIN WANG

Department of Meteorology, and IPRC, University of Hawaii at Manoa, Honolulu, Hawaii

JONG-GHAP JHUN

School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

BYUNG-KWON MOON

Division of Science Education/Institute of Science Education, Chonbuk National University, Jeonju, South Korea

(Manuscript received 13 April 2006, in final form 11 September 2006)

ABSTRACT

The 227-yr daily precipitation record gathered for Seoul, South Korea, represents one of the longest instrumental measurements, which provides an exceptional opportunity for detecting climate singularity (a property of phase locking to annual cycle) of extreme weather events and multidecadal–centennial variability of the rainy season structure. From late June to early September, the occurrence of heavy rain events shows a climatological quasi-biweekly oscillation. The rainy season characteristics, including the dates of onset, retreat, summit, and the duration, all show significant centennial variations. The rainy season summit shows a tendency toward delayed occurrence, which changed from the 37th pentad (P37; 30 June–4 July) during the 1778–1807 period to P44 (4–8 August) during the 1975–2004 period. The amplitude of the interannual (2–6 yr) variation of summer precipitation shows a prominent fluctuation with a 50-yr rhythm. A notable climatological break (around 9–13 August) divides the rainy season into a changma (Korean for continuous rain period) and a post-changma period. The major modes of subseasonal variability of the rainy season are characterized by an advanced changma and an enhanced post-changma, respectively. The former is dominated by biennial variation, whereas the latter has a major 5-yr spectral peak, suggesting that the processes leading to their variability are different. The occurrence of severe drought events exhibits a 4-yr spectral peak along with large power on a centennial time scale, while the severe flood events have a spectral peak at 3 and 19 yr, respectively. The remarkable climate variability in Seoul rainfall suggests that trends detected by using a 50-yr-or-shorter precipitation record likely reflect natural variability.

1. Introduction

The South Korean city of Seoul (37°34′N, 126°58′E), located at the geographic center of the East Asia (EA) monsoon region (20°–50°N, 100°–145°E), receives the largest amount of precipitation in the region (Wang and LinHo 2002). The year-to-year rainfall variability in Seoul station correlates significantly with the variability along the EA monsoon rain belt, stretching from the lower reach of the Yellow River to northern Japan (Fig. 1). An in-phase variation between northeastern India and Korea/Japan was noted in a longer record (e.g., Kripalani and Kulkarni 1997, 2001).

Instrumental measurements of precipitation were made from 1778 to 1907 using Chukwookee (meaning "rain-measuring device"), which closely resembles the modern rain gauge (Kim 1988). This official record is one of the earliest instrumental measurements in the world (Wada 1917; Kim 1988), and the reliability of the resulting Chukwookee data has been recognized since the work of Arakawa (1956). Scientists have used *monthly mean* precipitation data to investigate interannual variability (e.g., Cho 1978; Kim and Ha 1987) and climate change (Wang et al. 2006; Ha and Ha 2006).

Jhun and Moon (1997) compiled a *daily* rainfall

Corresponding author address: Prof. Jong-Ghap Jhun, School of Earth and Environmental Sciences, Seoul National University, Seoul 151-747, South Korea.
E-mail: jgjhun@snu.ac.kr

DOI: 10.1175/JCLI4123.1

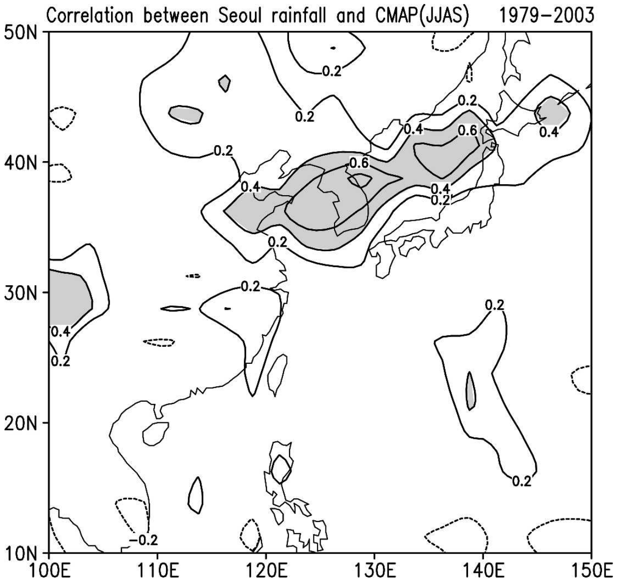


Fig. 1. Correlation map of the JJAS precipitation in East Asia with reference to Seoul's JJAS precipitation. The precipitation data are derived from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) for the period from 1979 to 2003 (Xie and Arkin 1997).

dataset based on the Chukwookee records (1778–1907) gathered by Lim et al. (1996). This high-resolution dataset is extremely valuable not only because of its long record and high accuracy but also because of its high temporal resolution. This dataset provides an exceptional opportunity for detecting the singularity (a property of phase locking to annual cycle) of extreme weather events and the multidecadal–centennial variability. Differently from Ha and Ha (2006), who used monthly data to focus on the interannual variability, here we focus on analysis of the variability of the rainy season's characteristics (onset, break, peak, and withdrawal) and rainy season structure. The results obtained from the present analysis provide new perspectives for deducing properly the trends associated with global warming in recent decades in Korea.

2. Dataset

The Chukwookee data used in the present study were originally recompiled by Lim et al. (1996) and are more reliable and complete than the Wada (1917) data (Jhun and Moon 1997; Park and Yadav 1998). The Chukwookee data of Lim et al. (1996) were derived from a set of official royal diaries from the Chosun Dynasty. These documents list the date of each precipitation event along with the starting and ending hours of precipitation, the total amount of rain during each event, and a description of rainfall intensity and cloud conditions. The dates and times of rainfall were originally recorded using the lunar calendar and have been converted into local times and dates based on the solar calendar. The ancient units used to measure the rainfall were chuck, chon, and poon, which correspond to 20 cm, 2 cm, and 2 mm, respectively. No decimals were recorded; thus, rain events of less than about 1 mm were neglected. The impacts of round-up errors on the climatological pentad mean precipitation, however, are expected to be negligible.

Jhun and Moon (1997) further derived a daily precipitation dataset. They first obtained hourly rainfall data by uniformly distributing the total rainfall amount of each event across each hour of the event. Daily rainfall data were further constructed from hourly data for the period of 1778–1907. Data for the beginning portion of the 1771–77 time period were excluded because the diary is partially missing; another period with missing data is the Korean War (1950–53).

The interpolation of the "event" rainfall to daily rainfall yields a proxy to real daily rainfall. The diurnal cycle derived from the hourly (Chukwookee) dataset agrees very well with the diurnal cycle derived from the modern rain gauge observation (Jung et al. 2001). The pentad mean and monthly mean precipitation calculated from the proxy daily data shows statistical consistence with their modern counterparts. Table 1 shows that the standard deviations of the monthly rainfall derived from the Chukwookee time frame (1778–1907) and the modern observation period (1908–2004) are quite comparable. The summer mean rainfalls for two periods are not significantly different from each other at the 0.05 significance level. It is also noted that there were two megadrought periods in the Seoul record (1778–1800 and 1875–1908), and both are consistent with the same drought periods occurring in the Shan-

Table 1. Statistics of rainfall (mm) for the Chosun Dynasty observation period (1778–1907) and modern observation period (1908–2004).

	Jun		Jul		Aug		Sep		Summer	
	Mean	Std dev	Mean	Std dev	Mean	Std dev	Mean	Std dev	Mean	Std dev
Chosun	129.6	92.3	347.8	221.4	264.0	172.9	120.4	112.6	861.8	356.8
Modern	142.1	109.4	372.1	198.8	287.6	200.7	144.8	107.7	946.5	319.5

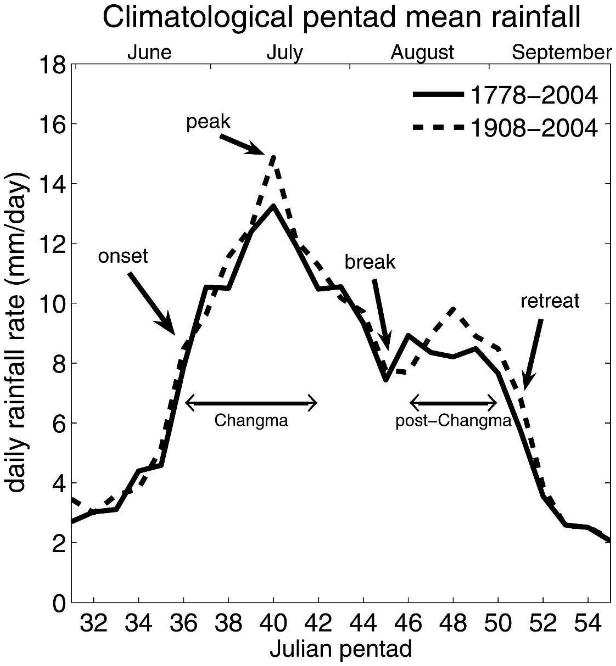


FIG. 2. Climatological mean pentad (5 day) rainfall rate for Seoul, averaged for the entire period (1778–2004; solid) and for the modern period (1908–2004; dashed). The climatological onset, peak, break, and retreat dates, as well as the changma and post-changma periods, are indicated.

dong province of China, which is located to the southwest of the Korean peninsula across the Yellow Sea. The Chinese dataset was based on reconstructed historic rainfall records derived from the Qing Dynasty (1644–1911) archives (Ge et al. 2005). During July and August, both Seoul and Shandong precipitations are governed by the advance of the same EA monsoon rain belt. Thus, the two historical megadroughts in Seoul may reflect a large-scale variation of the EA monsoon rainband.

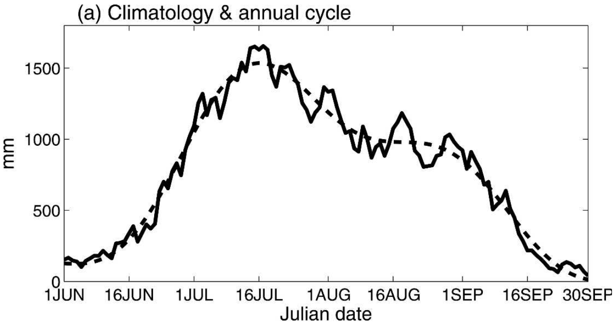
3. Characteristics and singularities of the climatological rainy season

Figure 2 shows the 227-yr averaged pentad rainfall distribution during June–September (JJAS). During this period, the pentad mean rainfall increased sharply, from 22.9 mm pentad^{-1} (or 4.6 mm day^{-1}) in pentad 35 (P35 hereafter, representing 20–24 June) to 39.4 mm pentad^{-1} (or 7.9 mm day^{-1}) in P36 (25–29 June), signifying the climatological onset of the rainy season around 25 June. This abrupt climatological onset is roughly 15 days later than the onset of the mei-yu in the lower reaches of the Yangtze River Valley and the onset of the baiu in southern Japan, which both occur in the early part of mid-June (Ding 1992; Japanese Meteorological Agency 2004). The peak of the summer rainfall occurred during P40 (15–19 July). The withdrawal of the rainy season is denoted by a rapid decrease in rainfall, from 38.3 mm in P50 to 17.8 mm in P52; thus, the mean rainy season retreat occurred during P51 (8–12 September).

Of note is the existence of a climatological monsoon "break" during P45 (9–13 August) and a late-summer revival of precipitation between P46 and P50 (14 August–7 September), an occurrence more evident in the modern record covering the period 1908–2004 (Fig. 2). The rainfall difference in P48 between Chosun and the modern periods is statistically significant at the 90% confidence level. The existence of a climatological monsoon break is a manifestation of a phase lock of dry weather in the annual cycle, or a monsoon singularity (Wang and Xu 1997). Because of this dry singularity, the Korean rainy season consists of one major rain surge occurring from late June to the beginning of August, referred to in Korean as the changma (meaning "continuous rain period"), and one secondary rainy period, which occurs from mid-August to early September and is here referred to as the post-changma period, for lack of a traditional term. As such, the post-changma rainfall is irregular and does not show a sharp maximum. This type of "double-peak" distribution of summer rainfall is commonly observed in other EA monsoon regions such as southern Japan, Taiwan, the subtropical western North Pacific, and the Indochina Peninsula (Wang and LinHo 2002). In these regions, the first peak is associated with the seasonal advance of the EA monsoon rainband, while the second peak reflects the influence of tropical cyclones (Wang and LinHo 2002).

Figure 3a shows an unexpected feature of the long-term climatology: the amount of torrential rainfall (greater than 50 mm day^{-1}) displays a climatological oscillation. If the slow annual cycle, defined by the first four Fourier harmonics (dashed curve in Fig. 3a), is removed, the resultant climatological oscillation can be more clearly seen (Fig. 3b). From late June to early September, torrential rainfall events tended to occur more frequently at the beginning and in the middle of a calendar month (i.e., 5 peaks occur around 2 July, 16 July, 1 August, 17 August, and 2 September, while 4 minima occur roughly in between these peaks). Ryu and Kripalani (2002) found that the variance explained by the 10–20-day oscillations is nearly double that of the 30–60-day oscillations in the summer monsoon rainfall over South Korea during the period of 1978–2000.

To test the statistical significance of this climatological oscillation, we used the Student's *t* test. The null hypothesis was that the oscillation's peaks, which are


(a) Climatology & annual cycle

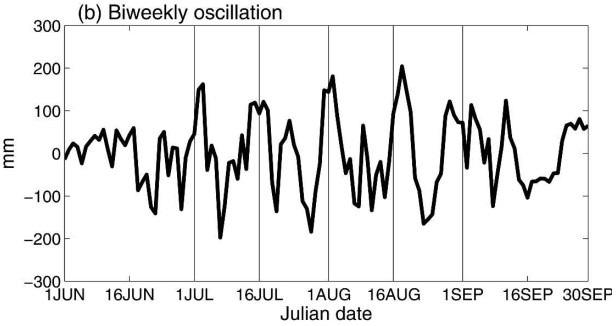

(b) Biweekly oscillation

FIG. 3. (a) Climatological 5-day running mean for the amount of torrential rain (defined as instances in which daily rainfall exceeds 50 mm). Slow annual cycle (dashed; defined by the first four Fourier harmonics plus annual mean). (b) Climatological biweekly oscillation of the torrential rain that is derived upon removing the slow annual cycle.

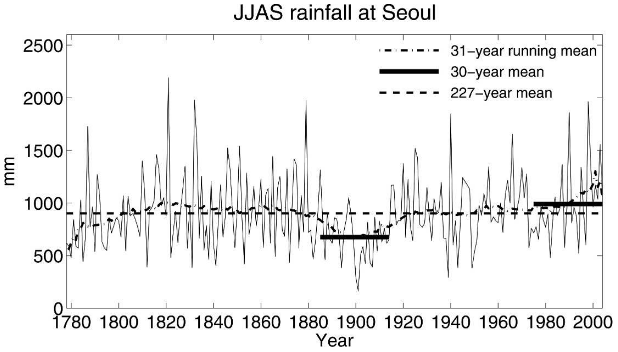


FIG. 4. Time series of JJAS rainfall for Seoul (1778–2004). The driest 30-yr period (1885–1914) and the wettest 30-yr period (1975–2004) are marked.

centered at a specific local maximum, are not significant from zero (slow annual cycle); in other words, these maxima are due to sampling errors. At a confidence level of 95%, we found that the test results for the aforementioned peaks in July and August reject the null hypothesis. Thus, the peaks and valleys associated with the biweekly oscillation represent statistically significant weather singularities. The results here imply that the heavy rainfall events tend to occur more frequently on specific fixed dates of the solar calendar. The cause, however, is unknown.

4. Multidecadal and centennial variations in rainy season characteristics

Figure 4 shows the time series for June–September precipitation in Seoul for the period of 1778–2004. The long-term mean and the standard deviation of the June–September rainfall for Seoul amount to 901 and 344 mm, respectively. The maximum June–September rainfall for Seoul was 2190 mm in 1821, in contrast to the driest summer, which had rainfall of 164 mm in 1901. This large amplitude fluctuation in summer rainfalls suggests that natural variability alone can be enormous, differing by up to 13 or 14 times.

Since the climatological conditions are often determined by a 30-yr averaged condition (World Meteorological Organization 1984, 1989; Guttman 1989), we calculated a 31-yr running mean to show the climate change of JJAS precipitation. The mean summer precipitations for the driest 30-yr period (1885–1914) and the wettest 30-yr period (1975–2004) differ by 315 mm, indicating that the summer rainfall has undergone considerable changes during the past 227 yr (Fig. 4). Kim et al. (2002) also reported that the monsoon rainfall over South Korea for the recent 30-yr period has been above normal.

In addition to changes in the total rainfall, the characteristics of the rainy season (the subseasonal distribution of rainfall and the season's onset, summit, break, and retreat dates) have also experienced remarkable changes over the past 227 yr. Information about the rainy season's characteristics is critical for planning farming activities and managing water resources. Figure 5 shows four 30-yr mean climatologies, constructed for the 2 driest (1778–1807 and 1885–1914) and 2 wettest epochs (1810–39 and 1975–2004). The rainfall difference between the two driest epochs and the two wettest epochs is found to be statistically significant, especially during P42–P50. A striking feature is that the timing of the peak rainy season has changed drastically from 1778 to 2004, moving from P37 (30 June–4 July) during the 1778–1807 period to P44 (4–8 August) during the 1975–2004 period.

Figure 6 reveals that the characteristics of the rainy season exhibit considerable multidecadal–centennial variations. The timing of the peak rainy season has changed slowly on a centennial time scale and shows a tendency toward delayed occurrence: during the late eighteenth century, the peak occurred within P37 (30 June–4 July), whereas it occurred around P44 (4–8 August) during the late twentieth century. In addition, the peak rain intensity shows an oscillation with a period of about 40–50 yr. The onset dates, as defined by the 30 mm pentad^{-1} contour, show a centennial variation

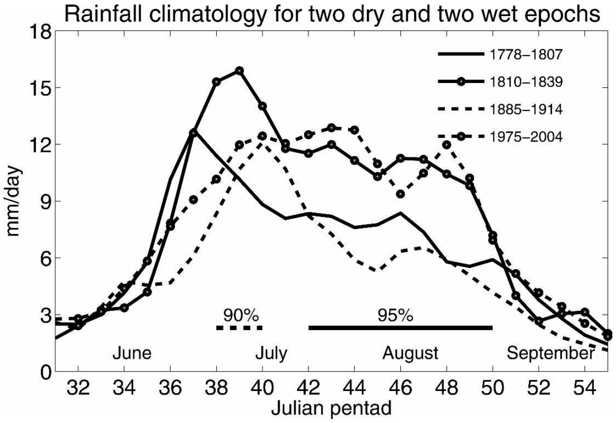


FIG. 5. Three-pentad running mean rainfall climatology derived from the two dry epochs (1778–1807 and 1885–1914), and the two wet epochs (1810–39 and 1975–2004), with large dots. The levels of statistical significance regarding the difference between the two driest and two wettest periods are indicated beneath the curve.

ranging from P35 to P37. The centennial variation in withdrawal dates is perhaps more evident. Interestingly, the phases of the onset date oscillation tend to be 180° out of phase with those of the withdrawal date, implying that the duration of the rainy season tends to be prolonged when the onset starts earlier than normal.

5. Interannual and decadal variability

To further provide an objective description of the changes in the subseasonal structure of the rainy season, we carried out an empirical orthogonal function (EOF) analysis of the yearly three-pentad running mean rainfall time series from P31 to P55 for the 227-yr data period. The three leading modes account for 25.1%, 14.8%, and 13.1% of the total variance, respectively. The first EOF mode has a single maximum within P41 and depicts an enhanced and prolonged changma (Fig. 7a). This mode resembles the structure of the typical monsoon rainy season with a single peak in the continental monsoon region. The second EOF mode, peaking in P39 and breaking in P43, represents an advanced changma with a near-normal post-changma. The third EOF mode, which has a major peak at P44 and a minor peak at P37, may be viewed as an enhanced (and advanced) post-changma with a weakened changma. The second (advanced changma) and third (enhanced post-changma) modes of variabil-

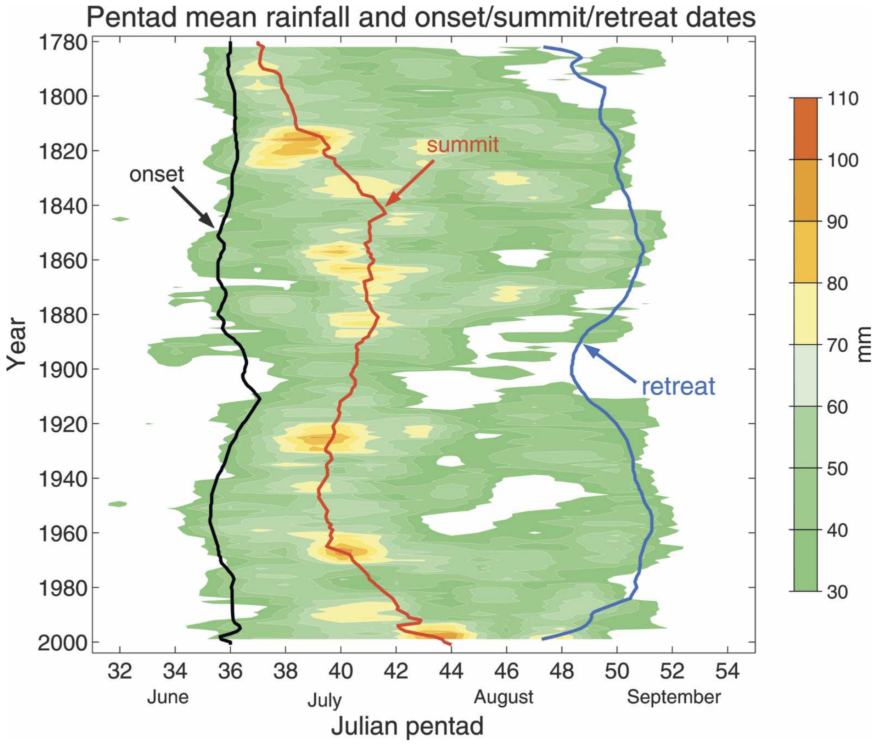


FIG. 6. Three-pentad weighted (1/4, 1/2, and 1/4, respectively), running mean rainfall from 1778 to 2004. An 11-yr running mean was applied to the rainfall time series at each fixed pentad in order to delineate climate variations in the subseasonal structure of the rainy season. The black, red, and blue curves depict 31-yr running mean dates for onset, summit, and retreat, respectively.

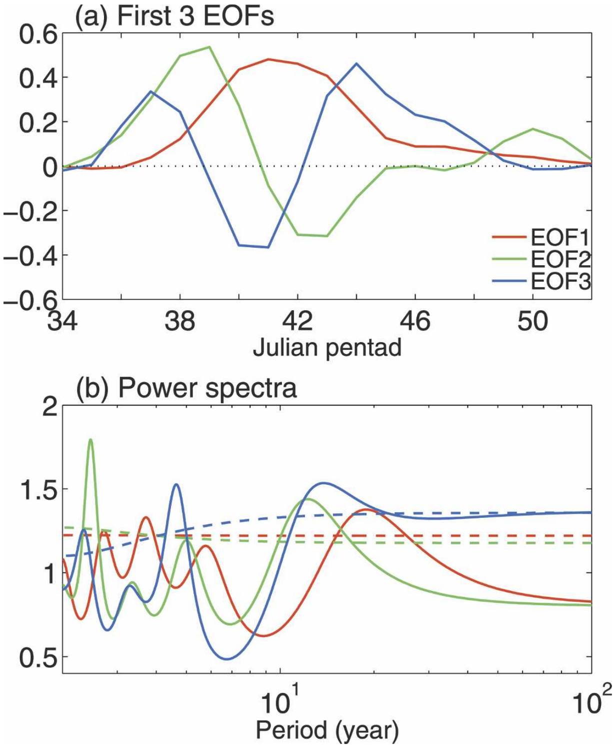


FIG. 7. (a) The subseasonal structure of the first three EOF modes of the three-pentad running mean rainfall. The red, green, and blue curves represent the first, second, and third modes, respectively. (b) The power spectrum density distribution of the first three principal components derived from the maximum entropy method.

ity are interesting because they are orthogonal to the typical rainy season and represent subseasonal fluctuations of the rainfall distribution within the rainy season or the variability of the rainy season structure.

All three principal components (PCs) of the EOF mode exhibit significant peaks on both the interannual (2–5 yr) time scale and the decadal (12–20 yr) time scale (Fig. 7b), indicating that the rainy season structural variability is dominated by interannual and decadal variations without significant trends. Their interannual variations are characterized by a quasi-biennial (2–3 yr) rhythm and a 4–5-yr rhythm, respectively. In particular, the second PC has a strong 2–3-yr peak while the third has a major peak around 5 yr, suggesting that the advanced changma has a strong quasi-biennial tendency, while the enhanced and advanced post-changma has a dominant 5-yr spectral peak.

The amplitude of the interannual variation of the combined changma and post-changma rainfall displays prominent multidecadal fluctuation. A Morlet wavelet analysis was applied to the time series of the Seoul summer precipitation. Figure 8a shows the local wavelet power spectrum normalized by standard deviation.

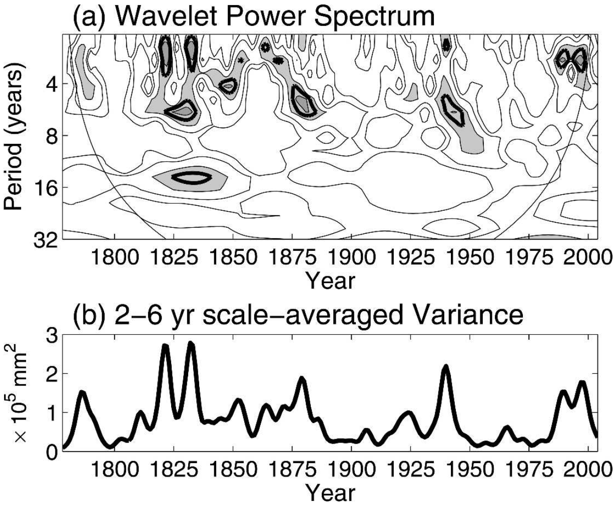


FIG. 8. Wavelet modulus analysis of the Seoul JJAS precipitation (1778–2004): (a) the local wavelet power spectrum normalized by standard deviation. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively; (b) the scale-averaged wavelet power over the 2–6-yr band.

Torrence and Compo (1998) provide a method of calculating statistical significance levels of the wavelet module. The thick lines on Fig. 8a indicate the powers that are significant at the 95% confidence level. The two thin solid curves to the left and right of the module distribution outline the areas where the analysis is contaminated by the "end effect" of the wavelet analysis (Wang and Wang 1996). Significant interannual variability is found in the 2–6-yr period. This result corroborates the previous results obtained from principal component analysis, which shows that all three leading PCs exhibit significant peaks on the interannual (2–5 yr) time scale. Important information provided by wavelet analysis is that the 2–6-yr scale-averaged variance displays a multidecadal fluctuation with a rhythm of about 50–60 yr (Fig. 8b). In comparison with Fig. 5, one observes that large (small) amplitude interannual variations occur during the wet (dry) period of the record.

6. Variability of extreme drought and flooding events

The classification of a devastating event—in this case, droughts and floods—depends on both the event's intensity and its duration. To quantify the persistent dry period and heavy rainy period, we used pentad rainfall to identify severe drought and flooding events. A severe drought was defined by the number of consecutive pentads during which 5-day rainfall was less than 20 mm; a devastating flood event was defined by the number of continuing pentads during which each pentad's

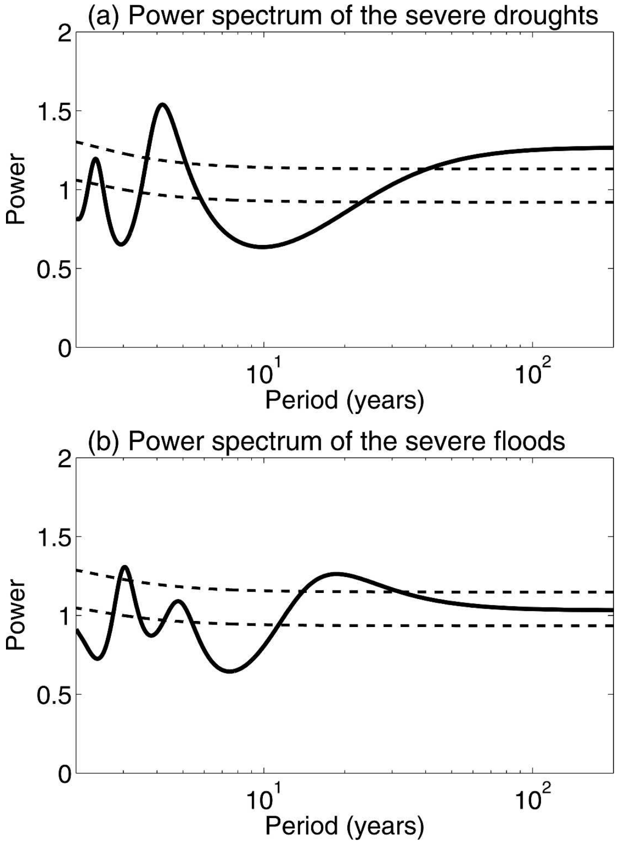


FIG. 9. Power spectrum for the severe (a) drought and (b) flood time series. A severe drought is defined by the maximum number of continuous pentads during P36–P50 in which the rainfall per pentad is less than 20 mm; a severe flood is defined according to rainfall per pentad of more than 80 mm. The dotted lines denote 95% significance.

rainfall was greater than 80 mm. The most severe drought occurred in 1894 and lasted 15 pentads; the most severe flood spanned 9 pentads and happened in 1879.

For brevity, the time series reflecting year-to-year variation of the severe drought and flooding events will be called the drought and flood index, respectively. The drought index exhibits a significant peak in the interannual time scale (about 4 yr; see Fig. 9a). On the other hand, the flood index shows strong peaks on both an interannual (about 3 yr) time scale and a decadal (around 19 yr) time scale (Fig. 9b). The analyses for the time series of the total number of pentads during P36–P50 in which the rainfall per pentad is less than 20 mm and more than 80 mm produce results similar to those shown in Fig. 9.

7. Summary and discussion

We have analyzed the 227-yr (1778–2004) daily instrumental precipitation data in Seoul. A number of significant weather events that are phase locked to the annual cycle were detected. They are the sudden onset around 25 June and a notable climatological monsoon break around 9–13 August that divides the rainy season into changma and post-changma rainy periods. Heavy rain events also tend to occur more frequently on fixed dates of the calendar year around 2 July, 16 July, 1 August, 17 August, and 2 September, showing a climatological oscillation with a quasi-biweekly rhythm during the rainy season. The finding of the *climatological biweekly oscillation* in heavy rain events is a surprise. To some extent, this finding is a local demonstration of the broad-scale monsoon singularities documented by Wang and Xu (1997) for the entire Asian monsoon region but with a much shorter record (17 yr). Whether or not this biweekly climatological oscillation links to large-scale circulation patterns warrants further investigation.

The 30-yr mean conditions exhibit remarkable changes in the past 227 yr in terms of the total amount of rainfall and the characteristics of the rainy season. This is due primarily to pronounced multidecadal–centennial variability. The dates of onset, retreat, and summit, as well as the duration of the rainy season, display centennial variability, while the amplitude of the interannual variations shows a prominent 50-yr fluctuation. The latter was detected by wavelet analysis. These rainy season changes primarily reflect natural variability on multidecadal and centennial time scales. The factors that give rise to the variability in the rainy season structure remain elusive. The subseasonal variability of the Seoul rainy season was investigated by EOF analysis of summer rainfall distribution in each summer for the 227-yr record. It is found that the subseasonal structural variations are primarily on the interannual (2–5 yr) and decadal (10–20 yr) time scales. Two major modes of variability were identified that deviate from a typical single-modal rainy season commonly seen in the continental monsoon region. The two modes represent an advanced changma and an enhanced post-changma condition, respectively. The advanced changma has a strong biennial tendency, whereas the enhanced post-changma activity has a major spectral peak every 4–5 yr. Using a recent record that covers a shorter time span, Tomita et al. (2004) found that the subtropical high and associated mei-yu/baiu have a strong biennial tendency.

Since the normal mei-yu/baiu leads Seoul changma by about 15 days and since the EOF 2 (advanced changma) leads Seoul normal changma by about 15 days, we consider that the EOF 2 reflects influences of the mei-yu front. The results here suggest that the mei-yu/baiu variability in early summer has a biennial tendency. The difference in the spectra between the EOF 2 and EOF 3 modes suggests that the processes controlling changma (and mei-yu/baiu) variability and post-changma variability are different. From a synoptic, meteorological point of view, changma rain is produced by weather systems along the EA subtropical front, while post-changma rain is often associated with passages of cold fronts, the influence of tropical cyclones, and/or the occurrence of mesoscale convective storms. The results here suggest that the mechanisms affecting interannual variations of the EA monsoon rainband and polar front/tropical cyclones are different. This has implications for the interpretation and prediction of summer rainfall variability in the East Asian monsoon region. Lee et al. (2005) showed that the summer rainfall in the EA monsoon region has two components—the Tropics-related rainfall and the midlatitude-related rainfall. The former component, which is associated with the Pacific–Japan pattern (Nitta 1987) or the East Asia–Pacific pattern (Huang and Sun 1992), reflects changma or mei-yu/baiu, while the latter component, which is associated with the Eurasian pattern (Wallace and Guztler 1981), reflects post-changma coming from polar front/mesoscale convective activities.

To quantify rainfall extreme, we defined a drought index as the maximum consecutive number of "dry" pentads during which pentad rainfall is below 20 mm and a flooding index as the maximum consecutive number of "wet" pentads during which pentad rainfall exceeds 80 mm for each June–September (JJAS) season. The drought index shows a spectral peak at 4 yr and large power on the centennial time scale, while the flood index has a spectral peak at 3 yr and a decadal peak at 19 yr. These extreme events do not show a significant trend over the entire record. For a more detailed analysis of the long-term trends in extreme precipitation events, the readers are referred to an accompanying paper by Wang et al. (2006). The remarkable multidecadal and centennial variations in Seoul rainfall suggest that the trend detected by using a 50-yr-or-shorter record in Korea and perhaps the East Asian monsoon region likely arises from natural variability.

Acknowledgments. This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-4205, and by the Eco-Technopia Project of the Ministry of Environment of Korea.

REFERENCES

Arakawa, H., 1956: On the secular variation of annual total rainfall at Seoul from 1770 to 1944. *Arch. Meteor. Geophys. Bioklimatol. Ser. B.,* **7** (2), 205–211.

Cho, H. K., 1978: Secular variation of the rainfall in South Korea. *Climatic Change and Food Production: International Symposium on Recent Climatic Change and Food Production Held October 4–8, 1976,* K. Takahashi and M. M. Yoshino, Eds., University of Tokyo Press, 25–39.

Ding, Y., 1992: Summer monsoon rainfalls in China. *J. Meteor. Soc. Japan,* **70,** 373–396.

Ge, Q.-S., J.-Y. Zheng, Z.-X. Hao, P.-Y. Zhang, and W.-C. Wang, 2005: Reconstruction of historical climate in China: High-resolution precipitation data from Qing Dynasty archives. *Bull. Amer. Meteor. Soc.,* **86,** 671–679.

Guttman, N. B., 1989: Statistical descriptors of climate. *Bull. Amer. Meteor. Soc.,* **70,** 602–607.

Ha, K.-J., and E. Ha, 2006: Climate change and interannual fluctuations in the long-term record of monthly precipitation for Seoul. *Int. J. Climatol.,* **26,** 607–618.

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

Japanese Meteorological Agency, 2004: Annual report of meteorology. Center for Support of Meteorological Service Rep., 273 pp.

Jhun, J.-G., and B.-K. Moon, 1997: Restorations and analyses of rainfall amount observed by Chukwookee (in Korean). *J. Korean Meteor. Soc.,* **33,** 691–707.

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. Climate,* **14,** 2989–3004.

Kim, B.-J., R. H. Kripalani, J.-H. Oh, and S.-E. Moon, 2002: Summer monsoon rainfall patterns over South Korea and associated circulation features. *Theor. Appl. Climatol.,* **72,** 65–74.

Kim, J.-W., and K.-J. Ha, 1987: Climatic changes and interannual fluctuations in the monthly amounts of precipitation at Seoul (in Korean). *J. Korean Meteor. Soc.,* **23,** 54–69.

Kim, S. S., 1988: Comments on the Chinese claim for the invention of Chukwookee (in Korean). *J. Korean Meteor. Soc.,* **24,** 427–440.

Kripalani, R. H., and A. Kulkarni, 1997: Rainfall variability over Southeast Asia—Connections with Indian monsoon and ENSO extremes: New perspectives. *Int. J. Climatol.,* **17,** 1155–1168.

——, and ——, 2001: Monsoon rainfall variations and teleconnections over South and East Asia. *Int. J. Climatol.,* **21,** 603–616.

Lee, E.-J., J.-G. Jhun, and C.-K. Park, 2005: Remote connection of the northeast Asian summer rainfall variation revealed by a newly defined monsoon index. *J. Climate,* **18,** 4381–4393.

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). Department of Atmospheric Sciences, Seoul National University Rep. KOSEF 93-0700-06-02-3, 165 pp.

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation. *J. Meteor. Soc. Japan,* **65,** 373–390.

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 Meteor. Soc.,* **34,** 459–465.

Ryu, C.-S., and R. H. Kripalani, 2002: Intraseasonal low frequency oscillations of summer monsoon rainfall in South Korea. *Korean J. Atmos. Sci.,* **5S,** 85–91.

Tomita, T., T. Yoshikane, and T. Yasunari, 2004: Biennial and lower-frequency variability observed in the early summer climate in the western North Pacific. *J. Climate,* **17,** 4254–4266.

Torrence, C., and G. P. Compo, 1998: A practical guide to wavelet analysis. *Bull. Amer. Meteor. Soc.,* **79,** 61–78.

Wada, Y., 1917: Report on old Korean observations (in Japanese). Korean Meteorological Observatory, 200 pp.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.,* **109,** 784–812.

Wang, B., and Y. Wang, 1996: Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. *J. Climate,* **9,** 1586–1598.

——, and X. Xu, 1997: Northern Hemisphere summer monsoon singularities and climatological intraseasonal oscillation. *J. Climate,* **10,** 1071–1085.

——, and LinHo, 2002: Rainy season of the Asian–Pacific summer monsoon. *J. Climate,* **15,** 386–398.

——, Q. Ding, and J.-G. Jhun, 2006: Trends in Seoul (1778–2004) summer precipitation. *Geophys. Res. Lett.,* **33,** L15803, doi:10.1029/2006GL026418.

World Meteorological Organization, 1984: Technical regulations. WMO Rep. 49, Geneva, Switzerland.

——, 1989: Calculation of monthly and annual 30-year standard normals. WCDP 10, WMO Tech. Doc. 341, Geneva, Switzerland, 9 pp.

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