Interpretation of the Transient Variations in the Time Series of Precipitation Amounts in Seoul, Korea. Part I: Diurnal Variation

HYUN-SOOK JUNG*
Forecast Research Laboratory, Meteorological Research Institute, Korea Meteorological Administration, Seoul, Korea

GYU-HO LIM
School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea

JAI-HO OH*
Forecast Research Laboratory, Meteorological Research Institute, Korea Meteorological Administration, Seoul, Korea

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ABSTRACT

Characteristics of temporal variations of precipitation for Seoul, Korea, have been examined using a 220-yr record. Precipitation records from modern rain gauges were used for 1908–96 together with the traditional Korean rain gauge precipitations for 1777–1907. The precipitation time series was partitioned into three precipitation regimes: wet period 1 (WP1; 1783–1883), the dry period (DP; 1884–1910), and wet period 2 (WP2; 1911–96). The basic features of the records were examined, and the diurnal variations derived from hourly precipitation were investigated. There were similarities between the statistical characteristics of the time series for WP1 and WP2, but the DP showed many statistical characteristics different from WP1 and WP2.

Diurnal cycles derived from the hourly precipitation rates in Seoul are generally consistent with previous observations in maritime areas, but some differences are apparent between the two WPs and the DP in the mean diurnal cycle and its seasonal variation. The WPs show similar characteristics of diurnal cycle with a peak near 0600 LST and a broad evening minimum around 1900–2400 LST during most of the years. The amplitude of the normalized diurnal cycle increases as precipitation intensity increases, and the timing for the morning peak is slightly earlier for the intense precipitation than for the light and moderate precipitation. In contrast, the morning maximum does not manifest itself clearly during the dry period. The diurnal cycle is seen in all seasons. The morning peak during Changma (the rainy season over Korea) results mainly from intense precipitation events, which are confined to a shorter period of the day than light or moderate precipitation.

1. Introduction

The Korean peninsula extends southward from the northeastern part of the vast Asian continent. About 70% of the territory is mountainous and the western and southern slopes are very gentle, forming plains. The climate of Korea is greatly controlled by monsoons. The annual precipitation in Korea (Fig. 1) depends largely on precipitation during the summer rainy season, which is strongly controlled by the East Asian summer monsoon system (Ramage 1971; Ding 1994; Kang et al. 1999).

Climatologically, heavy precipitation over Korea is mainly associated with two different synoptic-scale patterns (Lee et al. 1998). One pattern occurs with a quasi-stationary polar front over a period of 30–40 days from late June through July at all points of South Korea, and accounts for more than 40% of the annual precipitation at most stations (Lim 1997; Lee et al. 1998; Kim 1998). This is called Changma in Korea. The other occurs with a typhoon and the strong influences of the subtropical Pacific high over the period from middle August through early September, which is well known as the fall rainy season (Matsumoto 1992; Lim 1997; Kang et al. 1999).

The diurnal variability of precipitation has been a subject of many studies over various regions. Wallace (1975) and Dai et al. (1999) summarized and provided a comprehensive interpretation of the geographically organized distribution of amplitudes and phases of diurnal

*Current affiliation: Climate Research Laboratory, Meteorological Research Institute, Korea Meteorological Administration, Seoul, Korea.

†Current affiliation: Department of Environmental Atmospheric Sciences, Pukyang National University, Pusan, Korea.

Corresponding author address: Dr. Hyun-Sook Jung, Climate Research Laboratory, Korea Meteorological Administration, 460-18, Shindaebang-dong, Dongjak-gu, Seoul 156-720, Korea. E-mail: hsjung@metri.re.kr

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and semidiurnal oscillations in the frequency of occurrence of various precipitation types over the United States (Bleeker and Andre 1951; Hamilton 1981; Balling 1985; Riley et al. 1987; Winkler et al. 1988; Sangster 1989; Tucker 1993). In the Tropics, there exist a morning maximum of deep convection and rainfall (Gray and Jacobson 1977; McBride and Gray 1980; Murakami 1983; Haldar et al. 1991). However, the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) observations show an afternoon maximum in rainfall (Gray and Jacobson 1977; McGarry and Reed 1978; Woodley et al. 1980). Shinoda et al. (1999) analyzed, for the first time, the diurnal variations in 3-h rainfall for Niger in the West African Sahel and found that most differences between the wet and dry periods were found in the rainfall amounts and frequencies from midnight to morning (0300–0600 LST). Dai (2001) summarized the mechanism of the diurnal precipitation cycle (e.g., Gray and Jacobson 1977; Randall et al. 1991; Chen and Houze 1997; Sui et al. 1997). There are some studies for the coastal and inland regions in east Asia (Ramage 1952; Takeda and Iwasaki 1987) including Korea (Lim and Kwon 1998; Jung 1999), Japan (Fujibe 1988; Oki and Musiake 1994), and China (Kato et al. 1995). Dai (2001) shows a complete picture of the large-scale spatial patterns in the diurnal cycle of various types of precipitation on a global scale by analyzing 3-h weather reports. For example, showery precipitation and thunderstorms occur much more frequently in the late afternoon than other times over most land areas in all seasons and in the morning around 0600 LST over the North Pacific, the North Atlantic, and many other oceanic areas adjacent to continents. Ramage (1952) showed a morning maximum of precipitation with, if the location is favorable, an afternoon maximum as well over east Asia including five stations in South Korea. Lim and Kwon (1998) analyzed the horizontal structure of the diurnal variation of precipitation over the South Korean peninsula for 17 yr (1980–96) and found that the early morning or morn-
The annual and monthly precipitation of Seoul (37°34′N, 126°58′E), which is located in the western part of South Korea, before the year 1908 was analyzed in previous studies (Cho 1976; Cho and Na 1979; Kim and Ha 1987; Lim and Jung 1992; Jung and Lim 1994) based on Wada’s (1917) book, which contains monthly precipitation amounts from historical documents. In Korea, modern rain gauges were introduced in 1907. Since then, the modern rain gauges have been used for measuring the amount of precipitation. Recent studies (Lim and Jung 1992; Jung and Lim 1994; Cho et al. 1996; Park and Yadav 1998) also found that annual and monthly precipitation data from the traditional Korean rain gauge are reliable for long-term precipitation study. It was, however, impossible to analyze the diurnal variation of precipitation over the nineteenth and the early twentieth century until recently, when precipitation records by the traditional Korean rain gauge were recovered for the time intervals of a few hours or one-half of a day. Although Cho and Na (1979) reproduced the precipitation records by the traditional Korean rain gauge at time intervals of a few hours to a day from 1777 to 1800, the data received little attention.

The main objectives of this study are to introduce observational precipitation data for Korea, which are some of the longest in the world, and to examine the major characteristic features of the diurnal variation of hourly precipitation and the differences of the diurnal cycle among several categories of precipitation (light, moderate, and heavy) in Seoul (one station). Also, the unique feature of the precipitation data has been summarized by comparing the diurnal cycle of the wet periods with that of the dry period.

2. Data and methodology

The Korean government has been measuring quantitative precipitation for a long period of time. In fact, King Sejong, who was the fourth king of the Chosun Dynasty (1392–1910), invented Chugugi (1441), the first rain gauge in the world. During the Chosun Dynasty, the network of Chugugi had been maintained and the records were kept in the king’s diary (Kim 1988).

This study analyzed long-term precipitation records measured with the traditional Korean rain gauge for 131 yr (1777–1907) and with modern ones for 89 yr (1908–96) in Seoul. We used annual and hourly precipitation amounts to analyze the general characteristics of temporal variations including the diurnal variation for three different periods.

First, we created datasets of pseudohourly and annual precipitation amounts based on the precipitation records recovered by both Cho and Na (1979) for 1777–1800 and Lim et al. (1996) for 1801–1907. The term pseudohourly amount means that the traditional Korean rain gauge measured precipitation amounts not every hour, but measured the total accumulated amount for individual precipitation events together with the starting and ending times of days (i.e., duration), if precipitation events occurred. Therefore, we calculated the pseudohourly precipitation amount assuming that rainfall intensity is uniform during the corresponding event. We did not modify or correct (e.g., Groisman et al. 1991) the Chugugi data except for unit conversions.

The precipitation amount by the traditional Korean rain gauge was recorded with the Korean foot-rule such as Pun, Chi, and Cha, which approximately correspond to 2, 20, and 200 mm, respectively. For example, 1 Pun or more of precipitation was measured with the minimum resolution of Pun and the event with precipitation amount less than 2 mm was not measured. To compare the characteristics of the diurnal cycle during the later part of the Chosun Dynasty with those of the modern, we converted the original traditional Korean rain gauge records to those of modern ones with accuracy to 0.01 mm. No matter how many digits we keep in the conversion, the accuracy still remains at 1 Pun. This sounds more like a truncation problem. The missing values during the Korean War (1950–52) and for the years of 1800 and 1894 were not included in our analysis of the time series of precipitation.

The precipitation records contain interannual variability as well as seasonal variability. Hence, expression of the data in standardized anomalies can be more useful than direct comparison to find differences in diurnal cycles. Following Oki and Musiake (1994), the normalized diurnal cycle of precipitation at hour \( h \) in the \( x \)th year (month) can be defined as

\[
NDP(x, h) = \left[ \frac{\bar{p}(x, h)}{\frac{1}{24} \sum_{h'=1}^{24} \bar{p}(x, h')} - 1 \right],
\]

where \( \bar{p}(x, h) \) is the mean precipitation amount at hour \( h \) in the \( x \)th year (month), and is calculated by

\[
\bar{p}(x, h) = \sum_{d=1}^{n_d} p(d, h),
\]

where \( p(d, h) \) is the hourly precipitation amount (except...
for trace on a day and at hour , and is the number of days for individual years (months) for annual (monthly) amounts.

Similarly, the normalized diurnal cycle of the frequency of occurrence of precipitation can be defined as

\[
\text{NDF}(x, h) = \left[ \frac{\tilde{F}(x, h)}{\frac{1}{24} \sum_{h=1}^{24} \tilde{F}(x, h)} - 1 \right].
\]

where \( \tilde{F}(x, h) \) is the mean number of precipitation frequency at hour \( h \) in the \( x \)th year (month). The normalized diurnal cycle of each year (month) can be interpreted as the anomaly of the hourly precipitation rate (precipitation frequency) at hour \( h \). The normalized amplitude of 0.0 means the amplitude of the diurnal cycle at hour \( h \) is same as the daily mean. The normalized amplitudes of 0.5 and -0.5 correspond to 150% and 50% of the daily mean, respectively.

Previous studies (Wallace 1975; McGarry and Reed 1978; Dai 2001) used harmonic analysis to determine the amplitude and phases of the diurnal and semidiurnal cycles. Usually the diurnal variation of precipitation has a sudden increase or decrease and is highly skewed with a long tail; therefore, it is not feasible to describe the variation with the trigonometric functions, which are the basic units in harmonic analysis. Therefore, we used a simple 1-2-1 filter for smoothing to express the normalized diurnal cycle. In this study, local standard time (135°E meridian) is used throughout.

The frontal system related to the Asian summer monsoon is known as Changma. The Changma affects Korea during the June–August period. Onset and duration of the Changma season is determined by considering many variables, such as the amount of precipitation and cloudiness variations in the pressure systems, low-level wind flow, and weather conditions. To determine the mean Changma period for the later part of the Chosun Dynasty, which has no information except precipitation, we employed the variable block average (VBA) filter, which is a technique for automatically determining the positions of sudden changes in time series. The VBA filter is defined as the variable-width, nonoverlapping block average, and uses information obtained by applying the Haar transform on a fixed scale and as much as possible within-record transform positions (Howell 1995).

2 Trace means the event with a precipitation amount less than 0.1 mm h\(^{-1}\) and the event with a precipitation amount less than 2 mm per event for modern and Korean rain gauge, respectively.

3 The frequency of occurrence of precipitation is defined here as the number of measurable precipitation events except the trace events. It may be referred to as the precipitation frequency for short.

3. General characteristics of annual precipitation

The time series of the annual precipitation amount of Seoul is given in Fig. 2. The earlier part (1777–1907) of the data was derived from the pseudohourly precipitation record in the Seungjungwon-ilgee, which is the official diary of the Chosun Dynasty. The later part of the record (1908–96) was obtained from the Korea Meteorological Administration. Data from both types of rain gauges were connected only with a simple conversion of measuring units. The missing data during the Korean War (1950–52) and the years of 1800 and 1894 were interpolated linearly in time. Except for the dry period around 1900, when apparently smaller annual precipitation was recorded, there are no other significant discontinuities over the entire period of the time series. Note that there is no discontinuity in annual precipitation between the years of 1907 and 1908, when two time series of annual precipitation by the traditional Korean rain gauge and by the modern ones were connected without any modification.

To delineate decadal or interdecadal variations in the annual precipitation amount, we have produced a low-pass-filtered time series with 9-yr moving averages. When we look at the moving-averaged time series, we are led to conclude that the Seoul precipitation has a distinct dry period and other wet periods. From the low-pass-filtered time series and the amount of annual precipitation, we partitioned the entire period into three precipitation regimes, wet period 1 (WP1) for the period of 1783–1883, the dry period (DP) for the period of 1884–1910, and wet period 2 (WP2) for the period of 1911–96. WP1 and WP2 were significantly wetter than the DP and the employed criterion was the precipitation amount of 990 mm yr\(^{-1}\) in the time series of 9-yr moving-averaged means. The criterion was defined as annual mean precipitation for 1911–96 minus one-standard deviation (exactly 992.8 mm). WP1 and WP2 regimes include the years when annual precipitation exceeded 990 mm yr\(^{-1}\), and the years when annual precipitation was less than 990 mm yr\(^{-1}\) were classified as the DP.

Fig. 2. Time variations of annual precipitation amounts (mm yr\(^{-1}\)) in Seoul derived from the pseudohourly precipitation record by the traditional Korean rain gauge (1777–1907) and the modern rain gauges (1908–96). Thin and thick lines denote the annual precipitation amounts and low-pass-filtered values with 9-yr moving averages, respectively.
The beginning 6 yr with less than 990 mm yr\(^{-1}\) (Fig. 2) were not included in the statistical analysis even though it was a very interesting feature of the time series.

We analyzed the unfiltered time series to examine general characteristics of the selected regimes. The statistical parameters for each regime are summarized in Table 1. Missing data were omitted from statistical analyses. The annual mean precipitation amount for the DP is less than WP1 and WP2 by 350 and 420 mm yr\(^{-1}\), respectively. The coefficient of variation, which is the standard deviation divided by mean value, shows more fluctuations during WP1 than the DP and WP2. WP1 and WP2 have a distribution with positively skewed and large kurtosis, and the DP has a negatively skewed and small kurtosis distribution in comparison with the normal one.

WP1 and WP2 were similar in their statistical characteristics although the latter had precipitation amounts about 100 mm yr\(^{-1}\) higher than the former with a significance level of 0.5%. The measuring unit and standard method used with the traditional Korean rain gauge may have contributed to the differences. The traditional Korean rain gauge did not measure trace precipitation amounts (<2 mm). This could result in an undermeasurement of 35–40 mm yr\(^{-1}\) in liquid and another 40 mm yr\(^{-1}\) in the form of solid precipitation. When we tested the significance level of parameters for the three regimes shown in Table 1, the means of the WPs and the DP can be regarded as different with a significance level of 0.1% irrespective of WP1 and WP2. The means of WP1 and WP2 were statistically equivalent to each other.

### 4. Diurnal variations

#### a. Wet period 1 (1783–1883)

To investigate the qualitative features of diurnal precipitation variation for wet period 1, we calculated the composites of the diurnal cycle including all precipitation events except the traces. Figure 3 shows the normalized diurnal cycles of the averaged hourly precipitation rate and precipitation frequency as a function of the time of day for a day and plus an extra half day. The diurnal cycle of the hourly precipitation rate exhibits a pronounced morning peak at 0600 LST and an evening minimum around 1900–2100 LST, with normalized amplitudes of 0.51 and −0.32, respectively. The diurnal variation in the frequency of occurrence of precipitation, however, is apparently weaker than that of the hourly precipitation rate with a relatively flat maximum between 1000 LST and 1500 LST. The weak diurnal cycle of precipitation frequency and the discordance of the relative maximum of the frequency profile with that of the hourly precipitation rate suggest that the morning maximum in the diurnal cycle of the hourly precipitation rate results from precipitation intensity.

Figure 4 shows the time variation of the diurnal cycle of the normalized hourly precipitation rate throughout WP1 as a function of year. The diurnal cycle of the precipitation rate shows interannual variability (Fig. 4a). However, a peak appearance of hourly precipitation around 0600 LST is very consistent both in wet and dry years (Fig. 4b).

Monthly variations of the normalized hourly precipitation rate, and an annual variation of the mean monthly precipitation for the time period of WP1 are shown in Fig. 5, respectively. Previous studies for Asian summer monsoon regions indicated that a morning peak was dominant during the warm rainy season (Ramage 1952; Fujibe 1988; Oki and Musiake 1994). Current results

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**Table 1. Statistical parameters for three regimes of precipitation amount (mm yr\(^{-1}\)).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WP1 (1783–1883)</th>
<th>DP (1884–1910)</th>
<th>WP2 (1911–96)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1231.0</td>
<td>890.4</td>
<td>1316.5</td>
</tr>
<tr>
<td>Std dev</td>
<td>385.8</td>
<td>256.1</td>
<td>323.7</td>
</tr>
<tr>
<td>Variation</td>
<td>31.3</td>
<td>28.8</td>
<td>24.6</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.96</td>
<td>−0.08</td>
<td>0.55</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>1.16</td>
<td>−0.31</td>
<td>0.79</td>
</tr>
</tbody>
</table>
for Seoul, however, indicate that the morning precipitation maximum is evident not only for summer but for throughout the entire year (Fig. 5a). The evening precipitation minimum around 1900–2100 LST during the summer (June–August) is weaker than other seasons in the normalized seasonal diurnal cycle, so the magnitude of the diurnal variation of precipitation is relatively small during the summer. There is a distinct morning peak in the normalized diurnal cycle in every month regardless of the mean monthly precipitation amount (Fig. 5b) unlike earlier studies (Sangster 1989; Oki and Musiake 1994). Since the total precipitation amount during the summer exceeds 60% of the annual precipitation amount and precipitation is minimal from October to March in Seoul, the strong morning peak in other seasons has little impact on the annual precipitation amount.

Figure 6 shows the mean precipitation amount (mm day$^{-1}$) for the rainy season (June–September), variations of mean daily precipitation for the entire WP1, and a VBA-filtered mean daily precipitation. The VBA-filtered signal identifies the position in the time domain where the daily precipitation amount varies abruptly. The positive step change on 27 June approximately coincides with the average daily precipitation amount and the averaged Changma onset date for WP2 discussed below. The negative changes appear on 2 August, 22 August, and 10 September. Based on its variations as well as widely accepted climatology, 2 August was selected as the *Changma* end date. There was no secondary rainy period during the later part of the Chosun Dynasty, which may suggest an absence of significant typhoon activities and/or the clear southward movement of the *Changma* front from northeast China to the Korean peninsula in the last third of August through early September.

Figure 7 shows the normalized diurnal variations of the averaged hourly precipitation rate and the frequency...
Fig. 4. (Continued)

Fig. 5. (a) Monthly variations of the normalized hourly precipitation rate (mm h⁻¹ month⁻¹), (b) annual variation of the mean monthly precipitation (mm month⁻¹). The contour interval is 0.3 and positive values are shaded. Average value for (b) is dotted.
of occurrence of precipitation during the Changma period defined in WP1 for total [all measurable precipitation, $0.0 < P$ (mm h$^{-1}$)] and three different precipitation categories, respectively. The precipitation categories are $0.0 < P \leq 3.0$, $3.0 < P \leq 15.0$, and $P > 15.0$ (Table 2). All these precipitation categories show marked diurnal variations with a morning preference and late afternoon-nocturnal minimum, which does not vary significantly with precipitation intensity. The diurnal variations of the total hourly precipitation rate (Fig. 7a) and the precipitation frequency (Fig. 7e) for the Changma period are similar to those of moderate (category 2, Fig. 7c) and light precipitation events (category 1, Fig. 7f), respectively. As precipitation intensity increases, the normalized amplitude of the diurnal cycle also increases, with stronger diurnal modulation and the maximum amplitude shifting to earlier periods in the morning. Note that both the normalized values of the diurnal precipitation rate and precipitation frequency in the heavier precipitation category (Figs. 7d and 7h) have a maximum at 0600 LST, while the light precipitation activities appear over a broad period during the daytime (Figs. 7b and 7f). This implies that precipitation becomes confined to a shorter time extent of the day as the intensity increases.

b. Dry period (1884–1910)

Results shown in section 3 imply that there may exist some differences in the diurnal variation of precipitation between the WPs and the DP in amplitudes and phases. Since hourly precipitation data are not available for 1908–10, we composed a diurnal cycle for 1884–1907 to specify the characteristics of the diurnal variation of precipitation during the DP. Figures 8–12 are in the same format as Figs. 3–7.

The composite diurnal cycles for the hourly precipitation amount and the frequency of occurrence of precipitation appear to be in phase with each other in contrast to WP1 (Fig. 8). A weak minimum, instead of a maximum, appears during the morning, and slightly positive values appear over a broad time period from 0900 to 1600 LST and from 2300 to 0400 LST. As for WP1, however, the evening minimum around 2000 LST is clearly seen in both hourly precipitation rate and precipitation frequency, with normalized extremes of 0.31 (Fig. 8a) and 0.33 (Fig. 8b), respectively. The amplitude of the normalized diurnal cycle of the hourly precipitation rate is smaller than WP1 by 38% (Figs. 3a and 8a). The ratio between the amplitudes of the diurnal cycle of precipitation rate for WP1 and the DP is about 1.6, whereas the diurnal cycle of the precipitation frequency for the DP is about the same range as for WP1. This suggests that there are more reduced precipitation activities in the morning than the afternoons, and there

<table>
<thead>
<tr>
<th>Category</th>
<th>Precipitation rate (mm h$^{-1}$)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>$0.0 &lt; P \leq 3.0$</td>
</tr>
<tr>
<td>2</td>
<td>$3.0 &lt; P \leq 15.0$</td>
</tr>
<tr>
<td>3</td>
<td>$P &gt; 15.0$</td>
</tr>
</tbody>
</table>
is less effect of the precipitation frequency on the diurnal range of the hourly precipitation rate.

As expected, there are interannual variations in the diurnal cycle of the hourly precipitation rate (Fig. 9a). Most years have negative anomalies of the annual precipitation amount (Fig. 9b). The diurnal cycle of the hourly precipitation rate has a morning preference around 0500–0600 LST and a minimum around 1900–2100 LST until the mid-1890s. After that time it has a primary minimum around 1900–2100 LST and a secondary one around 0500–0600 LST, and positive values around 0100–0400 LST. The relative nocturnal preference seems to cause the depression in the morning.

Monthly variations of the normalized hourly precipitation rate during the DP (Fig. 10) are more obvious than during WP1. The normalized diurnal variation of the hourly precipitation rate is very weak during the rainy season (May–September) when compared to the dry season (October–April). It seems that precipitation occurred more frequently around 0300–0400 LST during the dry season in the DP. The evening precipitation minimum around 2000 LST appears throughout the year.

The results of VBA-filtered mean daily precipitation for the DP show that a positive step change on 7 July approximately coincides with the average daily precipitation amount (Fig. 11). The date is relatively late compared with WP1. Negative changes meet with the average daily precipitation amount on 5 August, 21 August, and 10 September. The Changma end date was selected as 5 August using the same criterion for WP1.

The diurnal variations of the total hourly precipitation rate and the precipitation frequency (Figs. 12a and 12e) during the Changma period of the DP are similar to those of moderate (category 2, Fig. 12c) and light pre-
c. Wet period 2 (1911–96)

It is important to investigate the diurnal cycle of precipitation during WP2, not only to understand its characteristics, but also to compare with the diurnal cycle derived from the hourly precipitation records from the traditional rain gauge. Since hourly precipitation data was not available for 1911–60, we composed a diurnal cycle for 1961–96 to examine diurnal characteristics of WP2. The analyzed period of 36 yr is reasonably long enough to make the results significant. Figures 13–17 are in the same format as Figs. 3–7.

Precipitation activity has a morning preference, and the composite diurnal cycles of the hourly precipitation rate for WP2 have characteristics similar to WP1 (Fig. 13). An hourly precipitation maximum around 0600 LST is evident, even though it is not as pronounced as in WP1; and a broad evening minimum is found around 1900–2400 LST. The diurnal cycles of the hourly precipitation rate and the precipitation frequency appear to be in phase similar to the DP cycle. Amplitude of the normalized diurnal cycle of the hourly precipitation rate is weaker than in WP1 (Figs. 3a and 13a).

The diurnal cycle for individual years during 1961–96 (Fig. 14a) is noisier than in WP1 and the DP, with above-average hourly precipitation from 0000 to 1200 LST and below-average hourly precipitation from 1200 to 2400 LST in the most of the years. Precipitation is more frequent before 1200 LST during the day throughout a year, and monthly variations of the normalized diurnal cycle are characterized by larger values from April to November in contrast to WP1 and the DP (Fig. 15). An evening peak of precipitation at inland stations in Japan is seen from May to September, when the weather over Japan is controlled by the subtropical Pacific high and affected by the south-
west monsoon (Oki and Musiake 1994). In Seoul, however, the amplitude of the secondary peak around 1600 LST is much smaller than the morning peak and negligible. Unlike the case of Japan, there is a late-evening precipitation minimum in Seoul.

The results of VBA filtered mean daily precipitation for WP2 (Fig. 16) show that a positive step change on 24 June coincides with the average daily precipitation amount similar to WP1. Negative changes meet with the average daily precipitation amount on 29 July and 5 September. Composites were constructed from 24 June to 29 July to examine the diurnal cycle during Changma period using the same criterion for WP1.

The composited diurnal cycle during the Changma period of WP2 (Fig. 17) shows weak precipitation activity around 1800–2400 LST except in the light category (Fig. 17b). The light and moderate precipitation categories (Figs. 17b and 17c) also show the diurnal variation with a morning preference, although they do not have great influence on the diurnal variation of the total hourly precipitation. The diurnal cycle of very intense precipitation (Fig. 17d) is similar to that of the total precipitation and has a marked preference in the early morning around 0500 LST. The morning maximum of the hourly precipitation rate occurs 1 or 2 h earlier when compared to WP1 (Fig. 7), although the phase shift to earlier times with increasing precipitation intensity is also present during WP2. It seems to suggest that lighter precipitation tends to follow heavy precipitation as seen in the storms. The normalized diurnal cycle of the precipitation frequency for intense precipitation has a maximum in the late morning around 0500 LST. Hence, the hourly precipitation maximum in the morning is due to intense precipitation activity. A weak increase in the heavier precipitation category around 1600 LST (Fig. 17d) may be a result of convective precipitation due to daytime solar heating. Considering the weak afternoon peak compared to the early morning peak, diurnal heating and cooling are less important than other unknown forcing mechanisms for the diurnal precipitation in Seoul. This is in contrast to the precipitation diurnal cycle over the southeastern United States (Wallace 1975; Dai et al. 1999) and many other lands.

d. Diurnal variation for the extreme precipitation years

The diurnal variation of the extreme precipitation years during WP2 is compared. Figure 18 shows the anomaly of the precipitation amount for the rainy season (June–September) during the period of 1961–96. The upper and the lower 10 percentile are defined as ex-
Fig. 14. Same as Fig. 4 but for WP2: (a) time variation of the mean diurnal cycle of the hourly precipitation rate (mm h\(^{-1}\) yr\(^{-1}\)) throughout WP2 as a function of year. Light shading denotes values less than \(-0.5\), and dark shading greater than 0.5 (contours begin at \(-0.5, 0.3, 0.3, 0.5, 0.8, \) and \(1.1\)). (b) Anomalies of the annual precipitation amount (mm yr\(^{-1}\); departure from mean for 1961–96).


As expected, the hourly precipitation rate and the precipitation frequency for wet years exceed those in dry years at every hour of the day (Figs. 19a and 19b). The largest differences in precipitation amount between the dry and wet years are seen around 0400–0500 LST and 1600 LST. The former is related with morning maximum and the latter to the secondary peak in wet-year precipitation, which appears to result from daytime solar heating. During the dry years, the afternoon peak is not evident, suggesting that summer afternoon convection is suppressed in dry years. The maximum value of the hourly precipitation rate around 0400–0500 LST for wet years (Fig. 19c) seems to be a result of intensive precipitation, considering the morning preference is less pronounced in the diurnal cycle of the precipitation frequency (Fig. 19d).

It is notable that the diurnal variation of extremely dry years is different from that of the DP (cf. Fig. 8). This implies that the atmospheric conditions during the DP cannot be fully understood by analyses of the same meteorological variables used to analyze WP2.

e. Potential effect of assumption (constant intensity)

It is important to recognize the potential effect of assumption (i.e., constant intensity) made during the reconstruction of the pseudohourly precipitation for the earlier part of the records. We have tested the assumption by looking at the hourly precipitation rate and the precipitation frequency from the reproduced records of the modern rain gauge. The reproduced records were made by assuming that 1) the intensity is uniform during the corresponding event, and then 2) the events with precipitation amount less than 2 mm were not added in the reproduced diurnal cycles. The reproduced diurnal cycle of hourly precipitation rate (figures not shown) still has similar characteristics with original ones in that it has morning maximum around 0500 LST and minimum around 2100 LST, and it is still noisier than that
of WP1. However, the reproduced diurnal cycle of the hourly precipitation rate has reduced amplitude for the morning maximum as a result of the first assumption, especially in the heavier precipitation category (about by 30%), while the reduction of precipitation frequency is evident in the light category as a result of the second assumption, especially during the morning.

5. Summary and discussion

In this study, we analyzed precipitation records of Seoul for a 220-yr period. Although there are large in-
The precipitation time series was partitioned into three precipitation regimes; that is, WP1 (1783–1883), the DP (1884–1910), and WP2 (1911–96). During the DP, annual precipitation is only about 70% of the climatological mean (1777–1996). Considering the effects of the measuring unit and standard method, we may conclude that annual precipitation during WP2 was not significantly different from WP1. While there are similarities between statistical characteristics of the time series for WP1 and WP2, the DP showed many statistical characteristics different from WP1 and WP2. As a result, we may conclude that the DP was climatologically different from both wet periods.

One of the objectives of this study was to assess the reliability of the pseudohourly precipitation data from the traditional Korean rain gauge. Results indicate that the data are sound enough to establish a climatology of diurnal variation for various Korean precipitation regimes, which could be used to investigate the characteristics of each precipitation category.

Diurnal cycles derived from the hourly precipitation amounts in Seoul are generally consistent with previous observations in maritime areas, but some differences were apparent between the two WPs and...
the DP in the mean diurnal cycle and its seasonal variation. The WPs show similar characteristics of diurnal cycle with a peak near 0600 LST and a broad evening minimum around 1900–2400 LST, even though peaks in WP2 were not as sharp as in WP1 and the diurnal cycle is noisier than that of WP1. This may be due to a number of factors. First, a lunar calendar with 2-h increments in which zodiac symbols are used to note the time of a day was used in the Chosun Dynasty (1392–1910). The low-resolution lunar calendar may be unable to resolve the diurnal timing as accurately as the modern calendar.

When the Chugugi data were converted into the pseudo-hourly data, the in-between time was taken as the start (or end) time of the precipitation event.4 It means that the converting method would enhance the sharp increase of the peak at 0600 LST in WP1. Second, light precipitation less than the Pun (2 mm) unit, which appears over a broad period during the daytime, based on modern records, was neglected. Last, the preference time for heavier precipitation activity may vary over morning hours due to the variability of precipitation mechanism. Although the normalized amplitude of the diurnal cycle for WP1 and WP2 shows considerable seasonal variation, the morning maximum can be found in all seasons. The morning maximum during the dry seasons supports a suggestion of Fujibe (1988) that precipitation in cool seasons is caused mainly by extratropical cyclones accompanied by large-scale cloud systems, and that the morning maximum seems to be a general characteristic of widespread precipitation in middle latitudes.

Characteristics of the daily precipitation time series during Changma (the rainy season over Korea) for WP1 were similar to those for WP2 in its time evolution except that no secondary rainy period was seen during WP1. For both WPs, the amplitude of the normalized diurnal cycle increases as precipitation intensity increases. The maximum amplitude occurs about 2–3 h earlier for the intensive precipitation than for the light and moderate precipitation. The morning peak during Changma results mainly from intense precipitation events, which is confined to a shorter period of the day than light or moderate precipitation. This result supports the suggestion of Lim and Kwon (1998) that the intensive precipitation may be more continuous in its style during the morning than during the daytime in general.

Possible explanations for the morning precipitation maximum over East Asia were discussed previously (Ramage 1952; Takeda and Iwasaki 1987; Misumi 1999). Lim and Kwon (1998) suggested that the effects of geography and land–sea breeze should not be considered as a fundamental physical process to regulate the diurnal precipitation variation. The fact that the heavier precipitation occurs more frequently suggests that more likely causes include mesoscale and large-scale forcing. The mesoscale cloud clusters, which originate in the northeastern part of China and have a tendency to form frequently from afternoon to evening during the warm season, driven by westerly winds may partly explain the morning maximum over the Korean peninsula. The convergence of low-level monsoonal flow and land–sea circulation may have a role in the intensification of the precipitation activity in coastal regions during the summer monsoon season.

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