A Spatiotemporal Analysis of Historical Droughts in Korea

DO-WOO KIM
National Institute of Meteorological Research, Korea Meteorological Administration, Seoul, South Korea

HI-RYONG BYUN
Department of Environmental Atmospheric Sciences, Pukyong National University, Busan, South Korea

KI-SEON CHOI
National Typhoon Center, Korea Meteorological Administration, Jeju, South Korea

SU-BIN OH
Department of Environmental Atmospheric Sciences, Pukyong National University, Busan, South Korea

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ABSTRACT

The climatological characteristics of drought in South Korea were investigated using daily precipitation data for 1777–2008. The effective drought index was used to quantify the drought intensity. As a result, five characteristics were discovered. First, South Korea can be divided into four drought subregions (the central, southern, and east coastal regions and Jeju Island) using hierarchical cluster analysis. Second, a map for long-term drought conditions in the four subregions is created that allows identification of the spatiotemporal distribution of droughts for the 231 yr at a glance. Third, droughts in South Korea have time scales that depend on the onset season. Spring (March–May) droughts tend to be short (≤200 days) because the summer (June–September) rainy season follows. Summer droughts tend to be long (>200 days) because the dry season (October–February) follows. In the dry season, droughts tend to be sustained or become severe rather than being initiated or relieved. Fourth, 5-, 14-, 34-, and 115-yr drought cycles were identified by spectral analysis. The 5-yr cycle was dominant in all of the regions, the 14-yr cycle was observed over the southern and east coastal regions, and the 34-yr cycle was observed over the central region. Fifth, the most extreme drought occurred in 1897–1903 (return period: 233 yr) and was associated with the 115-yr drought cycle. After this drought, severe droughts (return period of >10 yr) occurred in 1927–30, 1938–40, 1942–45, 1951–52, 1967–69, and 1994–96; they were caused by the consecutive shortage of summer rainfall for two or more years.

1. Introduction

Assessment of historical droughts and their spatiotemporal characteristics provides basic data for identifying the potential for droughts in the future. Most studies tend to focus on specific droughts, however, and relatively few studies have attempted to analyze scientifically, and thereafter summarize, the overall history of droughts. Therefore, it is difficult to compare the severities of present-day and past droughts. This study provides basic data on drought “climatology” by analyzing the spatiotemporal characteristics of droughts and summarizing historical droughts. The drought climatology of Korea is an appropriate subject for this study because the precipitation data recorded since 1777 constitute one of the longest records in the world.

Quantification of drought severity should be the first consideration when analyzing drought climatology. Considerable research efforts have gone into the quantification of drought severity, and, at present, there are more than 50 drought indices available today (Byun 2009). The most widely used indices are the Palmer drought severity index (PDSI; Palmer 1965) and the standardized precipitation index (SPI; McKee et al. 1993). Many studies have reported that the PDSI has less practicality and
accuracy in comparison with the SPI because of its complex empirical derivation and the fact that its underlying computation is based on the climate of the midwestern United States (Alley 1984; Akinremi and McGinn 1996; Keyantash and Dracup 2002). Therefore, the SPI was considered to be superior to the PDSI, solely on the basis of precipitation (Guttman 1998). Of late, the effective drought index (EDI; Byun and Wilhite 1999) is being used increasingly in drought studies (e.g., Boken et al. 2005; Kim and Byun 2006, 2009; Usman et al. 2005; Morid et al. 2007; Smakhtin and Hughes 2007; Akhtari et al. 2008). Like the SPI, the EDI is calculated using only precipitation, but the EDI has the following differences from SPI. First, it is calculated with a daily time step. Second, it utilizes a variable time period to sum precipitation. Although the basic summation period is one year, if the drought continues, the summation period extends to incorporate the additional days. Third, the precipitation is summed using the time-dependent reduction function. In other words, it is assumed that large volumes of recent precipitation remain, whereas large volumes of precipitation that took place long ago are lost. Studies comparing the EDI and the SPI have suggested that the EDI quantifies droughts more precisely than does the SPI (Morid et al. 2006; Pandey et al. 2007; Kim et al. 2009). In particular, Kim et al. (2009) proved that the EDI is superior to the SPI in monitoring both long-term and short-term droughts. Thus, in this study, drought intensity was quantified using EDI.

The second consideration while analyzing drought climatology is the method used to analyze the spatiotemporal characteristics of droughts. In such analyses, principal component analysis is mainly used for the analysis of spatial patterns of droughts (Italy: Bordi and Sutera 2002; Sicily: Bonaccorso et al. 2003; Spain: Vicente-Serrano et al. 2004; Iberian Peninsula: Vicente-Serrano 2006; Iran: Raziei et al. 2009), cluster analysis is used for regional divisions of drought (Iberian Peninsula: Vicente-Serrano 2006; Iran: Dezfuli et al. 2009), and wavelet and power spectral analysis are used for the analysis of drought cycles (United States: Diaz 1983; South Korea: Min et al. 2003; Czech Republic: Brázdíl et al. 2009). The drought climate of many countries has been investigated using these methods. Most studies have focused only on the analysis of the theoretically derived drought characteristics, however. Only a few studies have addressed factors such as location, time of occurrence, and severity of the droughts that occurred in the past. The following studies have provided macroscopic insights into historical droughts. Diaz (1983) and Andreadis et al. (2005) summarized droughts in the United States, and Lloyd-Hughes and Saunders (2002) and Briffa et al. (2009) outlined droughts in Europe. In particular, Diaz (1983) constructed a drought map that allows one to see the spatiotemporal distribution of droughts in the United States at a glance. This map has an inherent limitation, however: the regional division was based on administrative districts rather than on drought regions. This study takes a novel approach in that it analyzed the drought climatology from the following three aspects: First, this study covered drought climatology for 231 years, which is a much longer period than that considered by previous studies, which ranged from 35 at the minimum (Dezfuli et al. 2009; Raziei et al. 2009) to 126 years at the maximum (Brázdíl et al. 2009). Second, a drought map was constructed based on the division of homogeneous drought regions. Third, not only were the theoretically derived characteristics of drought analyzed, but the investigation also included an attempt to identify which historical severe drought events had developed in association with these characteristics.

Droughts in Korea have usually been examined in terms of the season and year of their occurrence. Byun and Han (1994) defined seasonal drought periods during which, climatologically, little rainfall (<2 mm) took place for periods of more than 14 days. They specified the periods of 23 May–13 June, 25 July–12 August, 23 September–25 October, and 29 November–28 March as the drought periods in spring, summer, autumn, and winter, respectively. They focused only on the climatological conditions, however, and did not investigate the annual or decadal variability of seasonal drought. Studies on the characteristics of a specific drought year revealed that the summer drought in 1982 was caused by the disappearance of changma (the summer rainy period) (Kang and Byun 2004) and that the summer drought in 1994 was caused by the rapid evolution of the summer season (Park and Schubert 1997). Some researchers have analyzed the common characteristics observed in several drought years. Kim and Byun (2006) found that summer droughts were related to blocking phenomena over the Okhotsk Sea and the development of the North Pacific Ocean high pressure center toward the north. Lee and Byun (2009) identified that spring drought was related to the location of the baroclinic region in the midlatitudes and south–north gradient of the sea surface temperature of the North Pacific Ocean. Because the analysis period was limited to single seasons, however, they did not consider when the droughts started and terminated or how extensively the droughts developed. Thus, the above studies did not provide sufficient data to estimate the occurrence of, and to prepare against, potential droughts.

Comprehensive studies on droughts in Korea have mainly dealt with the cycle of droughts. Min et al. (2003) found that the droughts occurred at intervals of 2–3 and 5–8 yr and that they have increased in severity since the
In this study, we have constructed a drought map that provides an overview of the drought history in South Korea. We have analyzed various features of the droughts in Korea, including the classification of drought subregions, the seasonal characteristics of droughts, the drought cycle, and the severity of historical droughts.

2. Data and methods

a. Precipitation data

Daily precipitation data have been observed from different years in different regions of South Korea (Fig. 1). The Seoul station has the longest precipitation record (1777–2008). Precipitation was measured from 1777 to 1907 by using the chukwookee (a traditional rain gauge of Korea), and the data were restored by Jhun and Moon (1997). The chukwookee cannot measure less than 2 mm of precipitation (Jung et al. 2000); moreover, it inaccurately measures the precipitation from snowfall (Jung et al. 2001). These two factors result in a total of about 80 mm of precipitation going undetected, on an annual average, which accounts for about 6% of the mean annual precipitation (1326 mm) in the twentieth century.

Precipitation observation by means of a rain gauge (modern instrument) began in 1907 at four stations. The number of observation stations has been increasing over time (Fig. 1a). Precipitation data measured at 60 stations all over the country are available since 1973. This study used the daily precipitation data measured at 1 station (chukwookee data in Seoul) from 1777 to 1907 (A), at 4 stations from 1907 to 1912 (B), at 6 stations from 1912 to 1949 (C), at 13 stations from 1949 to 1973 (D), and at 60 stations from 1973 to 2008.
stations from 1973 to 2008 (E) (Table 1). The reason that there is an overlap of 1 yr between two consecutive periods is that the precipitation data for the previous 365 days are required to calculate the EDI value. The precipitation data measured at five stations during the Korean War were partially omitted (Table 2). The period of missing observations is 27 months in total, or 1.0% of the total analysis period and 2.2% of the modern observation period. Among the 13 stations that existed in this period, the periods in which precipitation went simultaneously unmeasured across 4 stations, 3 stations, and 2 stations, were 2 months, 3 months, and 9 months in length, respectively. We replaced these missing data with the 30-yr average precipitation values for each calendar date, based upon data from 15 yr prior to 15 yr after the year of the missing data. Because the missing data are only a low percentage of the total analysis period, the effect of the missing data on the result of this study is insignificant.

The spatial distribution of climatological (1974–2008) annual rainfall is shown in Fig. 3a. The average of 60 stations is 1342 mm, and the standard deviation is 190 mm. Figure 3b shows the climatological (1974–2008) seasonal precipitation cycle averaged over 60 stations. Three distinct precipitation peaks are observed. The first peak appears during spring (March–May), which is called the spring rainy season (RS) (Byun and Lee 2002; Han and Byun 2006). The total precipitation during the spring RS is 260 mm (2.8 mm day\(^{-1}\)), which accounts for 18% of the annual precipitation. The period from June to September is the summer RS during which 66% (884 mm; 7.2 mm day\(^{-1}\)) of the annual precipitation occurs. The summer RS has two precipitation peaks, which are related to the passage of the east Asian monsoon front over the Korean peninsula in its development and retreat stages (Chen et al. 2004); the first peak is called changma.
and the second one is called kaul-changma. The period from October to February is the dry season (DS: 198 mm; 1.3 mm day$^{-1}$) without any definite precipitation peak. These characteristics of rainy seasons also appear in the available stations in each period (A, B, C, and D). In Seoul, however, the percentage of summer rainfall to yearly rainfall is higher.

b. Effective drought index

The EDI was used to quantify drought intensity. Effective precipitation (EP) is the summed value of daily precipitation with a time-dependent reduction function [Eq. (1)]. The EP is then compared with the climatological mean EP (MEP) [Eq. (2)], and the results were

![Figure 2: Interannual variation of the mean precipitation (1974–2008) of 1, 4, 6, 13, and 60 stations, whose precipitation data are available starting from 1777, 1907, 1912, 1949, and 1973, respectively. The $R^2$ values between the mean precipitation of 60 stations and those of 1, 4, 6, and 13 stations are indicated on the upper-left side. The thin gray line denotes $-1$ standard deviation from the mean precipitation of 60 stations (1033 mm).]

![Figure 3: Precipitation climatological means and seasonal cycle (1974–2008) in South Korea. (a) Spatial distribution of mean annual precipitation over 60 stations. (b) Daily precipitation (15-day running mean) averaged over 1, 4, 6, 13, and 60 stations at which precipitation data were recorded since 1777, 1907, 1912, and 1949, respectively.]
The three equations that were used are:

\[
\text{EP} = \frac{\sum_{i=1}^{n} \left( \frac{\sum_{m=1}^{n} P_m}{n} \right)}{n}
\]

(1)

\[
\text{DEP} = \text{EP} - \text{MEP}, \quad \text{and}
\]

(2)

\[
\text{EDI} = \text{DEP}[\text{ST}(\text{DEP})].
\]

(3)

In Eq. (1), \(i\) is the duration of summation and is equal to 365, which is the most commonly used precipitation cycle. Thus, for calculating the daily EDI value, the precipitation data collected over the previous 365 days are required. MEP and ST(DEP) represent the climatological mean of EP and the standard deviation of DEP for each calendar day, respectively. The calibration period for calculating MEP and ST(DEP) is recommended to be longer than 30 yr. If the DEP continues to be negative for more than 2 days, the duration of summation \(i\) is increased by the number of days for which the DEP is negative, which has no limit. Owing to this function, the EDI is able to consider continuity of drought without any time limitation. The “drought range” of the EDI indicates extreme drought if \(\text{EDI} \leq -2\), severe drought if \(-2.0 < \text{EDI} \leq -1.5\), and moderate drought if \(-1.5 < \text{EDI} \leq -1.0\). Near-normal conditions are indicated if \(-1.0 < \text{EDI} < 1.0\). For more details, refer to the research by Byun and Wilhite (1999).

The EDI for 1908–2008 was calculated on the basis of the calibration period from 1974 to 2008 (the twentieth calibration period) for which the precipitation data are available over the 60 stations. Because the precipitation data measured by the chukwookee are different from those measured by the modern rain gauge, the EDI for 1778–1907 was calculated on the basis of the calibration period from 1814 to 1848 (the nineteenth calibration period). Two calibration periods had the fifth highest value of 35-yr mean precipitation in each relevant period (1778–1907 and 1908–2008) (Fig. 4). The average precipitation for these two periods is 1291 and 1374 mm, respectively. Considering that the annual precipitation that cannot be observed using the chukwookee is about 80 mm, the difference in the mean precipitation between the two calibration periods is not significant.

c. Drought event and its return period

A drought event was defined as the period in which the minimum EDI value is less than \(-1.0\). The onset of drought was defined as the date on which the EDI first drops below 0, and secession of drought was defined as the date on which the EDI last exceeds this value while maintaining a negative value after the onset. The duration of drought was defined as the period between the onset and secession dates. The frequency analysis of the drought events based on the EDI, calculated using daily precipitation data over 60 stations from 1974 to 2008, indicated that about 20% of the droughts were temporarily relieved within a week and redeveloped thereafter. An example of temporary relief from drought is presented in Fig. 5. In 1977, Seoul experienced a severe drought because the precipitation during the latter part
(August and September) of the summer RS was 59% less than an average year, and the drought continued for a long time because the precipitation during the following dry season (October–February) was not enough to end the drought. On 9 March 1978, an exceptional precipitation of 34 mm day\(^{-1}\) occurred and the EDI rose rapidly to a positive value. The precipitation shortage continued again, however, and eventually the precipitation during the spring RS in 1978 was 60% less than the average year. As a consequence, the drought began on 25 July 1977, was temporarily relieved for one day on 9 March 1978, and continued until 24 June 1978. This example illustrates well that even though an exceptional one-day precipitation could bring temporary relief, if no or low precipitation days continue after that, the water resource generated by the precipitation is lost over time because of outflow and evaporation and drought aggravates rapidly again. Although such a detailed description of a drought situation is appropriate for monitoring of drought, the percentage of short-term droughts can increase abnormally when one deals with drought climatology over a long period. To reduce such high-frequency variations, this study calculated the EDI using 15-day running mean daily precipitation.

The statistical return period of drought events was estimated for the quantitative assessment of the severity of historical droughts. The return period of a specific drought case can be presented by the reciprocal of the exceedance probability of that case:

\[
T = \frac{1}{P(X > x_T)} = \frac{1}{1 - P(X \leq x_T)},
\]

where \(x_T\) denotes the magnitude of the event having a return period \(T\). The drought variable \(x\) used in this study represents the duration. Kim et al. (2003) suggested that the drought duration can be analyzed from the partial duration series of independent cases because droughts sometimes last for more than 1 yr. The distribution of a partial duration series could be converted to an equivalent distribution for an annual exceedance series by using partial duration series methods (Eagleson 1972; Willems 2000; Kim et al. 2003). If the cumulative distribution function of drought durations \(d\) is represented by \(F(d)\), the return period \(T_d\) of the given drought is defined as

\[
T_d \text{ (years)} = \frac{N}{n[1 - F(d)]} = \frac{1}{\theta[1 - F(d)]},
\]

where \(\theta = n/N\), \(N = \) total length of the observed EDI (years), and \(n = \) total number of drought events \(d\) during \(N\). The cumulative probability was estimated using mean rank approximation:

\[
F(d) = i/(n + 1),
\]

where \(i\) is the rank order.

3. Construction of long-term drought map

A hierarchical cluster analysis was conducted on the EDI datasets for the period from 1974 to 2008, over the 60 stations, by using the between-group linkage method and Pearson correlation (Fig. 6). The correlation between merged clusters gradually reduced as 60 single-member clusters were merged step by step into one cluster of 60 members (Fig. 6a). The highest reduction ratio is obtained when four clusters are merged into three clusters. This implies that the most appropriate number of clusters in South Korea is four. Figure 6b shows the spatial distribution of four clusters. The drought subregions in
South Korea are largely classified into the central region (R1; 21 stations), the southern region (R2; 30 stations), the east coastal region (R3; 6 stations), and Jeju Island (R4; 3 stations). Such a classification is similar to the result of Park et al. (2009), who classified the climate zones considering both air temperature and rainfall in Korea.

In this study, we collected all available precipitation data from 1777 to 2008 for each region, considering the increasing number of observation stations over time (Table 1). Then, the national EDI (N-EDI) and the regional EDIs (R-EDIs) were calculated from the precipitation averaged over South Korea and the drought subregions (R1, R2, R3, and R4), respectively. Based on the N-EDI and R-EDIs, a long-term drought map of South Korea was created (Fig. 7), which allows us to identify the spatiotemporal distribution of droughts for 231 yr at a glance. The ability of the EDIs (1stn-, 4stn-, 6stn-, and 13stn-EDI) that were calculated from the mean precipitations of 1–13 stations to represent the EDI from the data of all 60 stations (60stn-EDI) was verified. The $R^2$ values between the 60stn-EDI and the 1stn-, 4stn-, 6stn-, and 13stn-EDI for the period of 1974–2008 were 0.49, 0.87, 0.91, and 0.93, which are similar to the results in Fig. 2.

**Historical severe droughts**

On the basis of the N-EDI from 1778 to 2008, a total of 114 drought cases were defined and the statistical return period for each case was estimated (Fig. 8). We can deduce the overall historical occurrences of droughts in South Korea by analyzing Figs. 7 and 8 together. There were 23 severe droughts that had return periods equal to or longer than 10 yr. Among them, eight severe droughts were concentrated between the 1880s and 1900s. In particular, the 1897–1903 drought was the severest drought in the entire analysis period, with a return period of 233 yr. Severe droughts were also frequent between the 1770s and 1780s.

In the period between 1925 and 2008, for which the data of four drought subregions are all available, six severe droughts occurred (July 1927–February 1930, June 1938–July 1940, May 1942–March 1945, June 1951–December 1952, May 1967–January 1969, and February 1994–August 1995). Among them, the severest case was the May 1942–March 1945 drought (return period: 77.7 yr). This drought developed nationwide, but it was relieved about 11 months earlier in R3 and about 4 months later in R4. Regional differences in the drought intensity are found in other severe droughts as well. The July 1927–February 1930 drought (return period: 46.6 yr) developed more intensively in R3 and started about 18 months later in R4. Regional differences in the drought intensity are found in other severe droughts as well. The May 1967–January 1969 drought (return period: 13.7 yr) was relatively weaker in R1. The February 1994–August 1995 drought was temporarily relieved for about 20 days and then developed again from September 1995 to March 1996. Figure 7 shows that this relief was limited to R1 rather than being a nationwide phenomenon. In R2 and R3, drought continued from February 1994 to March 1996. If the drought
of February 1994–March 1996 is regarded as a single drought case, it has a return period of 23.1 yr. The droughts of June 1938–July 1940 (return period: 23.3 yr), June 1951–December 1952 (return period: 10.1 yr), and February 1994–August 1995 (return period: 9.7 yr) were relatively weaker in R4.

4. Seasonal characteristics of drought

A histogram of the durations of 114 droughts between 1778 and 2008 is presented in Fig. 9a. The frequency of short-term droughts with durations of about 50 days was the highest. The frequency decreases as the duration nears 200 days. The frequency increases again, however, as the duration increases from 200 to 400 days, and the second frequency peak occurs in the long-term drought bin of about 350–400 days. This bimodal pattern of frequency distribution can be seen more clearly in R1 and R2 than in R3 and R4 (Fig. 9b).

Figure 10a presents the scatter diagram of 114 drought durations versus the onset seasons. It is seen that 54% of all droughts occurred during the summer RS (see Table 3). Droughts also occurred frequently in the spring RS (40%). A small number of droughts (6%) occurred during the DS. During the spring RS, the frequency of short-term (≤200 days) drought (67%) was higher than that of long-term (>200 days) drought (33%). During the summer RS, however, the frequency of long-term drought (79%) was substantially higher than that of short-term drought (21%). Because the spring RS is followed by the summer RS with abundant rainfall on an average, the droughts during the spring RS tend to last for a short period of less than 200 days. On the other hand, because the DS, which has no definite precipitation peak, follows the summer RS, the droughts during the summer RS tend to continue for a long term of over 200 days. In the summer RS, the droughts that started during June and July are classified into short-term droughts relieved by precipitation during August and September and long-term droughts that are not relieved. Most droughts that started during August and September continued for over 200 days. In the DS, droughts tend to be sustained or they become severe rather than being initiated or relieved. The results of the drought frequency analysis in the drought
subregions are represented by the numbers in parentheses in Table 3. The features of the short-term droughts in the spring RS and those of the long-term droughts in the summer RS, in the four subregions, were found to be similar. This is observed more prominently in R1 and R2 (Fig. 10b); 64% (R1) and 63% (R2) of the droughts in the spring RS were short-term droughts, and 81% (R1) and 71% (R2) of the droughts in the summer RS were long-term droughts. The reason for this appears to be that the seasonal difference in precipitation amount between the summer RS and the DS is more evident in R1 and R2 than in R3 and R4 (not shown).

Figure 11 shows the seasonal precipitation anomalies in 24 severe droughts (including the 1994–96 drought) that have return periods of longer than 10 yr. Of these 24 droughts, 20 began because of a shortage of rainfall during the summer RS [June–September (JJAS)]. All cases were intensified by consecutive shortages of rainfall during the spring RS [March–May (MAM)] and the summer RS of the following year. In the cases of the 1781–84, 1840–42, 1881–84, 1927–30, and 1942–45 droughts, the shortage of rainfall during the spring RS and the summer RS continued for one year longer and developed into extreme droughts, with return periods of longer than 10 yr.

![Figure 8](https://example.com/fig8.png)

**FIG. 8.** Return period and duration of observed droughts. Droughts are defined by the N-EDI from 1778 to 2008.

![Figure 9](https://example.com/fig9.png)

**FIG. 9.** Histogram of observed drought durations. Droughts are defined by (a) the N-EDI from 1778 to 2008 and (b) the R-EDIs from 1908 to 2008.
In the case of the 1897–1903 drought, which was the severest drought in 231 yr, the shortage of rainfall continued for more than 5 yr with no seasonal differences.

5. Long-term variability of drought

a. 1778–2008

Figure 4b shows the time series of the monthly mean EDI in Seoul from 1778 to 2008. Extremely long term dry periods were observed from 1778 to 1786 and from 1880 to 1913, which are hereinafter referred as D18 and D19, respectively. Byun et al. (2008) analyzed the frequency of rituals conducted for rain during drought periods in the Choson–Wangjo–Sillok (CSWJS: Royal Diary of Chosun Dynasty, 1392–1928; see online at http://sillok.history.go.kr/etc/english.jsp) and suggested that D18 started from 1771. The mean annual precipitations in D18 and D19 are 814 and 910 mm, respectively, which correspond to 63% and 70% of the mean annual precipitation (1291 mm) in the nineteenth calibration period. During D18 and D19, droughts occurred five times [5.6 (10 yr)] and 19 times [5.9 (10 yr)], respectively.

The other periods excluding D18 and D19—that is, 1787–1879 (N19; 93 yr) and 1914–2008 (N20; 95 yr)—can be regarded as normal periods. The mean annual precipitations in N19 and N20 are 1257 and 1338 mm, respectively. Considering that about 80 mm is missing on average in the annual measurement of precipitation before 1908, the mean annual precipitations in these two periods are similar. Nevertheless, there is a large difference in the drought frequencies in these two periods: 33 times [3.5 (10 yr)] in N19 and 57 times [6.0 (10 yr)] in N20. The box plots of drought duration during these two periods are shown in Fig. 12a. The droughts in N20 are divided into short-term and long-term droughts by a period of about 200 days. In N19, however, the median value of drought duration is much shorter.

<table>
<thead>
<tr>
<th>Duration of</th>
<th>Total</th>
<th>Spring RS: Mar–May</th>
<th>Summer RS: Jun–Sep</th>
<th>DS: Oct–Feb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 yr</td>
<td>40 (36, 52, 31, 44)</td>
<td>54 (52, 41, 49, 29)</td>
<td>6 (13, 7, 20, 27)</td>
</tr>
<tr>
<td></td>
<td>200 days</td>
<td>67 (64, 63, 57, 62)</td>
<td>21 (19, 29, 41, 36)</td>
<td>62 (38, 50, 29, 62)</td>
</tr>
<tr>
<td></td>
<td>&gt;200 days</td>
<td>33 (36, 37, 43, 38)</td>
<td>79 (81, 71, 59, 64)</td>
<td>38 (62, 50, 71, 38)</td>
</tr>
</tbody>
</table>
the drought duration was 358 days, which is substantially longer than that of N20, and the points in the scatterplot are concentrated around the median value. This implies that short-term droughts were as frequent as long-term droughts in N20, whereas mainly long-term droughts occurred in N19. Hence, the drought frequency in N19 is lower than that in N20. It was revealed in section 4 that long-term droughts occurred mostly because of a shortage of rainfall during the summer RS. Figure 12b compares the distribution of rainfall during the summer RS between N19 and N20. In these two periods, the upper quantile and median values of the summer RS rainfall are similar to each other but the lower quantile in N19 (667 mm) is much smaller than that in N20 (777 mm). This shows that the shortage of rainfall during the summer RS was more frequent in N19 than in N20.

The wavelet power spectrum for the monthly mean Seoul EDI is presented in Fig. 13a. Strong wavelet power
is found in four period bands. The first period band is about 105–125 yr, which is related to D18 and D19. This decadal-scale cycle was also indicated by Byun et al. (2008). Through an analysis of CSWJS, (1392–1928), they showed that the droughts related to this cycle occurred around 1405, 1529, and 1653 as well. The second period band is about 37–62 yr. Strong power appeared around the 60-yr period in the early 1800s, but the period became shorter over time and strong power appears around the 37-yr period in recent years. The third period band is about 16 yr, but the statistical significance level is not high. The last period band is about 6 yr, which is well known as the Korean drought cycle (e.g., Jhun and Moon 1997; Byun et al. 2008). The power is not steady in this period; instead, strong and weak cycles are repeated. The power of this cycle was very weak in the 1850–60s and 1960–70s.

The linear trend of Seoul-EDI for 231 yr is 0.015 (10 yr)$^{-1}$, which is significant at the 99% confidence level. This is because the time series begins from D18, however. The linear trend from 1787, which is the first year of N19, is not statistically significant.

b. 1908–2008

The wavelet power spectrum for the monthly mean N-EDI from 1908 to 2008 is presented in Fig. 13b. The wavelet power appears strong in the period bands of 31–37 yr (about 34 yr), 13–16 yr (about 14.5 yr), and 4–6 yr (about 5 yr). These drought cycles are similar to those that appeared in Seoul during the period from 1778 to 2008, but they differ slightly in bandwidth and power distribution. In the period band of about 34 yr, the strength of the power remained steady for 101 yr. In the period band of about 14.5 yr, the power discontinued.
During the 1920s, and the period and power increased from 1930 to the recent years. In the period band of about 5 yr, the power was weak in the 1960s.

To determine in which region these three drought cycles are more predominant, we performed spectral analysis of the monthly mean R-EDIs using the multitaper method (e.g., Ghil et al. 2002) (Fig. 14). The cycle of about 5 yr is commonly found in the four subregions. The 4–6-yr bandpass-filtered time series of the monthly mean N-EDI (Fig. 15a) reveals that the minimum peaks of the monthly mean EDI match well with the minimum peaks of the filtered time series, except for the 1960s. The droughts of 1978, 1983, 1988, 1992, 1996, and 2001, over the last 30 yr, correspond to this drought cycle. The cycle of about 14 yr (11–17 yr) appears in R2 (Fig. 14b). Figure 15b shows the 11–17-yr bandpass-filtered time series of monthly mean R2-EDI. Even though the minimum peaks of the monthly mean EDI do not match with the minimum peaks of the filtered time series, we can see that severe droughts developed mostly when the filtered time series had negative values. In particular, all six severe droughts with return periods of longer than 10 yr in N20 occurred in the negative phase of this cycle. A 14-yr drought cycle is also found in R3 (Fig. 14c). A 12-yr drought cycle, which is similar to the 14-yr drought cycle, was also reported by Byun et al. (2008) who directly measured the intervals of severe droughts and calculated the drought cycles. The cycle of about 34 yr (28–41 yr) appears in R1 (Fig. 14a). Figure 15c shows the 34-yr bandpass-filtered time series of monthly mean R1-EDI. The three dry periods of 1908–22, 1938–54, and 1973–89 are related to this cycle. Byun et al. (2008) also reported the cycle of 38 yr, which is similar to this cycle. According to them, the droughts of 1906, 1944, and 1982 correspond to this cycle. The droughts in 1944 and 1982 also correspond well to the cycle of 34 yr derived in this study. The drought in 1906 is slightly out of the 34-yr cycle. The drought in 1909 is closer to the 34-yr cycle than is the drought in 1906.

The linear trend of N-EDI for 101 yr is 0.074 (10 yr)$^{-1}$, which is significant at the 99% confidence level. This is also because the time series begins from D19, however. The linear trend in N20 (last 95 yr) is not significant. Thus, additional analysis is required to determine whether this wetting trend is associated with global
warming or is a part of the century-scale variability of the precipitation climate. Meanwhile, the increasing trend in the drought intensity after 1980 during the period of 1951–96, revealed by Min et al. (2003), is considered to be a part of long-term variability rather than a linear trend, since a humid climate continued from 1996 until recent years. Regional trends were 0.084, 0.049, 0.093, and 0.039 (10 yr)$^{-1}$ in R1, R2, R3, and R4, respectively.
the strongest being in R3 and the weakest being in R4.

6. Summary and conclusions

This study has presented an overview of the historical droughts in Korea from 1778 to 2008. We used all available precipitation data over South Korea including the chukwookee data in Seoul (1777–1907). The drought intensity was quantified by using the effective drought index on the basis of 15-day moving-average daily precipitation. South Korea was divided into four homogeneous drought regions: central, southern, east coastal, and Jeju Island. On the basis of the regional division of drought, a drought map was constructed to obtain an overview of the spatiotemporal distribution of the droughts that occurred in the past 231 yr. A total of 114 droughts \[0.49 (10 \text{ yr})^{-1}\] were detected from the drought map, and their seasonality and long-term variability were analyzed.

The time scale of droughts is divided into short term (36%) and long term (64%) by a period of about 200 days, which is related to the seasonal cycle of precipitation. The drought caused by insufficient precipitation during the spring rainy season (March–May) is mainly relieved during the following summer rainy season (June–September); 67% of droughts are short-term droughts. The droughts caused by insufficient precipitation during the summer rainy season tend to continue for a long time until the next spring rainy season because the period from October to February (dry season) is climatically dry; 79% of the droughts are long-term droughts.

It is found that droughts in Korea occurred on 5-, 14-, 34-, and 115-yr cycles. The 5-yr cycle appears in all four of the drought subregions, whereas the 14-yr cycle is only significant in the southern and east coastal regions and the 34-yr cycle is only significant in the central region. Although 115-yr cycle can be analyzed only for Seoul, for which 231 yr of data are available, this cycle is regarded as a nationwide phenomenon because the droughts associated with this cycle continued for very long times and with high intensity.

The most severe drought occurred from 1899 to 1903 (return period: 233 yr), which falls in the extremely long-term dry period (1880–1913; D19). After D19, six severe droughts (return period of \(\geq 10 \text{ yr}\)) occurred: 1927–30, 1938–40, 1942–45, 1951–52, 1967–69, and 1994–96. All six severe droughts developed during the negative phase (dry/drought) of the 14-yr drought cycle. Therefore, it is supposed that the severe droughts occurred under substantial influence of the 14-yr drought cycle. The main cause of the six droughts was consecutive shortages of summer (JJAS) rainfall for two or more years. From this, it can be hypothesized that the 14-yr drought cycle is linked with the decadal-scale variability of summer rainfall. In fact, we performed spectral analysis on the time series of summer rainfall for 1908–2008 and confirmed the existence of a 14-yr cycle (Fig. 16). This cycle did not appear in other seasons. Meanwhile, the seasonality of the 5-, 34-, and 115-yr drought cycles were also analyzed and were found to have appeared regardless of the season. Therefore, if subsequent studies analyze the 14-yr drought cycle in association with the decadal-scale variability of summer rainfall, they could uncover the cause and mechanism of this cycle more easily than those of other drought cycles.

In this study, the EDI was calculated on the basis of the 15-day moving-average daily precipitation data to reduce the high-frequency variation. In addition, the EDI calculation results using raw daily precipitation data and 31-day moving-average daily precipitation data were compared. Also, in these two types of EDI data, the short-term and long-term droughts were divided by a period of about 200 days. In the EDI data calculated using raw daily precipitation, however, the percentage of short-term droughts increased (62%) and therefore the drought frequency increased approximately twofold \[9.6 (10 \text{ yr})^{-1}\]. In this case, the long-term drought characteristic of summer is very weak. On the other hand, the EDI data calculated with 31-day moving-average daily precipitation show a high percentage of long-term droughts (80%) and therefore the drought frequency decreases to 3.7 (10 \text{ yr})^{-1}. In this case, the short-term drought characteristic of spring does not appear. Time-scale selection for measuring the drought intensity has been a long-standing problem in drought research. Therefore, the SPI measures the drought intensity on various time scales (e.g., 1–48 months). It is
difficult, however, to consider all of the relevant indices in drought climate research. Because the EDI overcame this limitation in many aspects, it allows monitoring of both long-term and short-term droughts with one index (Byun and Wilhite 1999; Kim et al. 2009). For the analysis of long-term climate data, however, the use of a moving-average or monthly-average EDI will produce better results, as in this study. More in-depth consideration of this issue is required in subsequent studies.

This study analyzed the spatiotemporal features of droughts in Korea and systematically summarized the historical records of droughts. It has become easier for future studies on droughts to select drought cases that have common characteristics or to find past droughts that are similar to some current drought. Therefore, drought studies in South Korea can now progress faster. It is expected that the division of homogeneous drought regions, the seasonality of droughts, and the statistical return period of historical droughts could be used as the basic data for establishing countermeasures to droughts in South Korea in the future. In addition, the regional drought cycles would provide clues to the prediction of droughts.

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