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Appraisal of Drought Characteristics of Representative Drought Indices using Meteorological Variables

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Abstract

In order to efficiently utilize meteorological drought indices, meteorological variables were compared with drought characteristics from the widely known Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). The results of this study indicate that SPI overestimated drought severity and SPEI overestimated drought frequency and length under the same weather conditions. For droughts of high severity and short duration, the shortage of precipitation was the dominant cause for the occurrence of drought. For investigation on drought duration, it was revealed that precipitation was the dominant variable influencing droughts at short durations. The effect of precipitation on drought decreased at long durations, with the effect of Potential Evapotranspiration (PET) on drought became important. For investigation on drought severity, it was revealed that drought severity was proportional to precipitation in both SPI and SPEI, but other meteorological variables did not have a significant relationship with drought severity. These results mean that the magnitudes of the two drought indices changes in different meteorological regimes and it is possible to contribute to the quantitative decision and the combination of drought indices for meteorological drought.

Keywords: *SPI, SPEI, drought characteristics, meteorological variables*

1. Introduction

Meteorological drought occurs earlier than agricultural or hydrologic drought, because it is not induced by human activity but by precipitation shortages. Because meteorological drought is at the forefront of drought propagation, it has been widely used in drought forecasting and analysis. Representative meteorological drought indices are the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), both of which are derived using the same procedure. The concept applied is very similar to that used for the calculation of current shortage relative to the average level. After Vicente-Serrano *et al.* (2010) proposed the SPEI based on precipitation and evapotranspiration, many studies have been carried out globally. Kim *et al.* (2012) evaluated drought severity in South Korea using observed climate and SPEI, and compared it to historical drought records. Kim *et al.* (2013) projected changes in future drought trends in South Korea using RCP8.5 and SPEI. Hernandez and Uddameri (2014) assessed drought in southern Texas using SPEI. Yu *et al.* (2014) applied a trend analysis for drought severity and frequency in China using SPEI. Chen and Sun (2015) analyzed SPEI's sensitivity to precipitation and temperature. Vicente-Serrano *et al.* (2015) analyzed the effect of precipitation and evapotranspiration on drought indices such as SPEI, RDI, and the Standardized Palmer Drought Index (SPDI) under different climates. Won *et al*. (2016) compared the results of SPEI and the Reconnaissance Drought Index (RDI) in the Han River basin in South Korea.

It is not easy to clearly define the beginning and end of a drought. Further, the possible causes of drought range from precipitation shortage to river discharge deficit. Therefore, drought analysis employs appropriate drought indices that include suitable variables. Previous studies have recommended adopting a complementary strategy rather than comparing drought indices. They advocate the conjunctive use of SPI and SPEI by comparative analysis. Jeong *et al.* (2014) confirmed the role of temperature in drought projection on North America's GCM (Global Circulation Model) by applying SPI and SPEI. Bachmair *et al.* (2015) examined the link between hydro-meteorological indicators and drought indices (SPI, SPEI) through the development of the EDII (European Drought Impact report Inventory). Lee *et al*. (2015) showed the high correlation between meteorological drought indices (SPI, SPEI) and the hydrologic drought index (SDI) by comparing these drought indices. Touma *et al.* (2015) projected future

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drought using 15 GCM scenarios with SPI, SPEI, SRI, and SDDI. Wang *et al*. (2015) compared the changes in severity of historical drought in China using SPI and SPEI. Xu *et al.* (2015) compared the severity, length, and spatio-temporal variation of drought in China using SPI, SPEI, and RDI. Baek *et al.* (2016) used SPI and VSIA (Vegetation Stress Index Anomaly) for monitoring and analyzing agricultural drought. Kim and Chung (2017) analyzed peak drought severity and drought duration to assess the lag time of peak drought severity between several drought indices, such as SPI, SPEI, and SDI.

Studies comparing SPI and SPEI have been performed, but the similarity and differences between the two indices based on meteorological variables has not been evaluated. In order to achieve complementary utilization of drought indices, the differences among the drought indices according to changes in meteorological variables should be quantified. It is necessary to establish guidelines based on such quantization researches for recommending some appropriate drought indices under current climate conditions and prospective changes to these conditions. Therefore, in this study, to investigate the differences between SPI and SPEI under the same climate, we calculated 3-, 6-, 9-, and 12-month SPI and SPEI for 60 sites in South Korea, and compared the spatial distribution of skewness, which is the difference between the SPI and SPEI. Moreover, the effects of meteorological variables on drought characteristics from SPI and SPEI were analyzed.

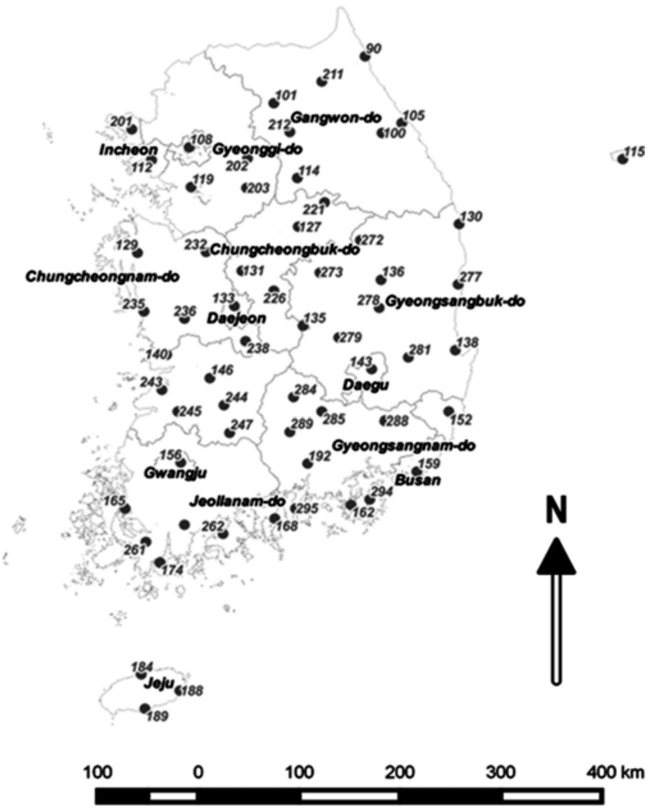

Fig. 1. Location of KMA ASOS 60 Weather Stations of South Korea

2. Methods

2.1 Data

Data on precipitation, temperature, wind speed, humidity, vapor pressure, and sunshine duration for a 43-yr period (1973-2015) were collected from 60 ASOS (Automated Surface Observing System) weather stations of KMA (Korea Meteorological Administration) (Fig. 1). Fig. 2 shows the spatial distribution of annual average precipitation and Potential Evapotranspiration (PET). Spatially averaged annual precipitation depth was 1335.9 mm yr^{-1}, and annual precipitation was higher along the south coast, in JeJu and Gangneung, than in Gyeongbuk-do. The spatial variation of precipitation was large. PET, which was estimated using the FAO (Food and Agriculture Organization of the United Nations) Penman-Monteith method as discussed by Allen *et al*. (1998), was larger in the southern districts than the central districts. Annual average PET was spatially distributed in accordance with latitude. Vicente-Serrano *et al.* (2010) suggested Thornthwaite equation for calculating PET because only temperature is needed for input variable. In this study, with enough meteorological observed data, the world-wide standard method for reference evapotranspiration,

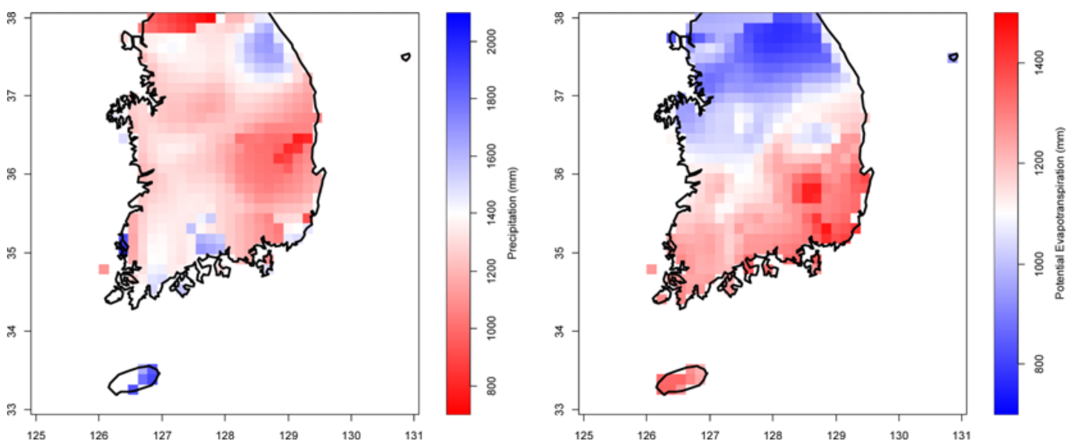

Fig. 2. Annual Averaged Precipitation (left) and Potential Evapotranspiration (right) of 1973 ~ 2015 for 60 ASOS Weather Stations

Penman-Monteith equation is applied.

2.2 SPI and SPEI

SPI employs a standardized progression of the probability distribution (e.g. gamma) related to cumulated monthly precipitation. Guttman (1998) suggested a Pearson Type-III (PT-III) distribution as the recommended probability distribution, but any extreme distribution function can be used if suitable for cumulative monthly precipitation. SPEI follows the same progression as SPI except for the input variable. SPEI uses the difference of precipitation and potential evapotranspiration (D = P − PET) instead of precipitation. For calculating PET, the Thornthwaite (1948) model was suggested by Vicente-Serrano *et al.* (2010) because of simplicity of calculation and easy data collection.

The process of SPEI calculation discussed by Vicente-Serrano *et al*. (2010) can be summarized as follow: Surplus accumulation of a climate water balance as the difference between the precipitation P and PET for the month i, which means deficit D_i, is calculated using:

$$D_i = P_i - PET_i \tag{1}$$

Drought duration, appropriate aggregation time step, is denoted by t_d. For the monthly deficit time series of $D_i(i = 1, 2, ..., i, i + 1, ..., n)$, the t_d months accumulated deficit (DS_i) of the ith month ($i \geq t_d$) is:

$$DS_i = \sum_{j=i-t_d+1}^{j=i} D_j \tag{2}$$

The water balance time series, accumulated deficit DS_i, is fitted into a log-logistic probability distribution:

$$g(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)\left[1+\left(\frac{x-\gamma}{\alpha}\right)\right]^{-2} \tag{3}$$

$$G(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \tag{4}$$

Where α, β, and γ are scale, shape, and origin parameters, respectively. With $G(x)$, SPEI can easily obtained as the standardized values of $G(x)$.

3. Analysis of the Differences between SPI and SPEI

3.1 Characteristics of Drought from SPI and SPEI

Table 1 presents the characteristics of drought events by the threshold level of the meteorological drought indices, SPI and SPEI, during 1973-2015 in South Korea. We calculated drought characteristics based on the theory of Yevjevich (1967) counting the water shortage events under the threshold, at an SPEI value of '-1.0'. In this chapter, drought was considered to have occurred when SPI or SPEI values were lower than -1.0. For both SPI and SPEI, drought frequency and severity decreased, whereas drought length increased with increasing drought duration, because the wet seasons were added to the moving window in the SPI and SPEI calculations. It was found that SPI showed higher severity than SPEI, whereas SPEI showed greater frequency and longer duration than SPI. This was because the variation in PET was smaller than that of precipitation and the variation in precipitation decreased when the time series of PET was considered together. Therefore, the droughts of SPEI showed moderate severity but greater frequency than those of SPI.

3.2 Statistical Analysis for Difference of SPI and SPEI

Figures 3 and 4 show the spatial distributions of the skewness, which is the difference between SPI and SPEI (SPI-SPEI). Because it is difficult to obtain meaningful results using the average and standard deviation for the difference between SPI and SPEI, as SPI and SPEI are standardized, we employed a skewness map. The skewness map explains how the distribution skewed and which tail is thicker. Spatial distributions of the skewness for the difference between SPI and SPEI (SPI-SPEI) are shown for the entire study periods (Fig. 3) and for drought periods (Fig. 4), in order to compare the characteristics of drought periods and non-drought periods. Drought events were defined to have occurred when SPI or SPEI values were lower than -1.0. Drought duration was increased progressively from 3 months, to 6, 9, and 12 months in order to investigate the influences of drought duration on drought characteristics. The legend in the figures is fixed from -1.5 to 1.5 to facilitate absolute comparisons between figures. A negative skew means a thick left-tail distribution and a lower SPI value, which means that SPI estimates such condition more significantly than SPEI, whereas a positive skew means a thick right-tail distribution and a lower SPEI value.

In Fig. 3, for the entire study period, skewness increases according to drought durations with spatially averaged skewnesses of -0.1128, 0.1338, 0.1630, and 0.1623. In Fig. 4, for drought period, skewness similarly increases according to drought durations with spatially averaged skewnesses of -0.6804, -0.3128, -0.2034,

Table 1. Drought Frequency, Length, and Severity of SPI and SPEI During 1973-2015 for 3, 6, 9, 12-month in South Korea

Drought duration	SPI			SPEI		
	Frequency	Length	Severity	Frequency	Length	Severity
3-month	41.5	1.9	-1.45	43.6	2.0	-1.37
6-month	31.6	2.6	-1.41	33.6	2.6	-1.35
9-month	23.1	3.5	-1.38	24.1	3.7	-1.33
12-month	17.7	4.7	-1.33	18.8	4.8	-1.29

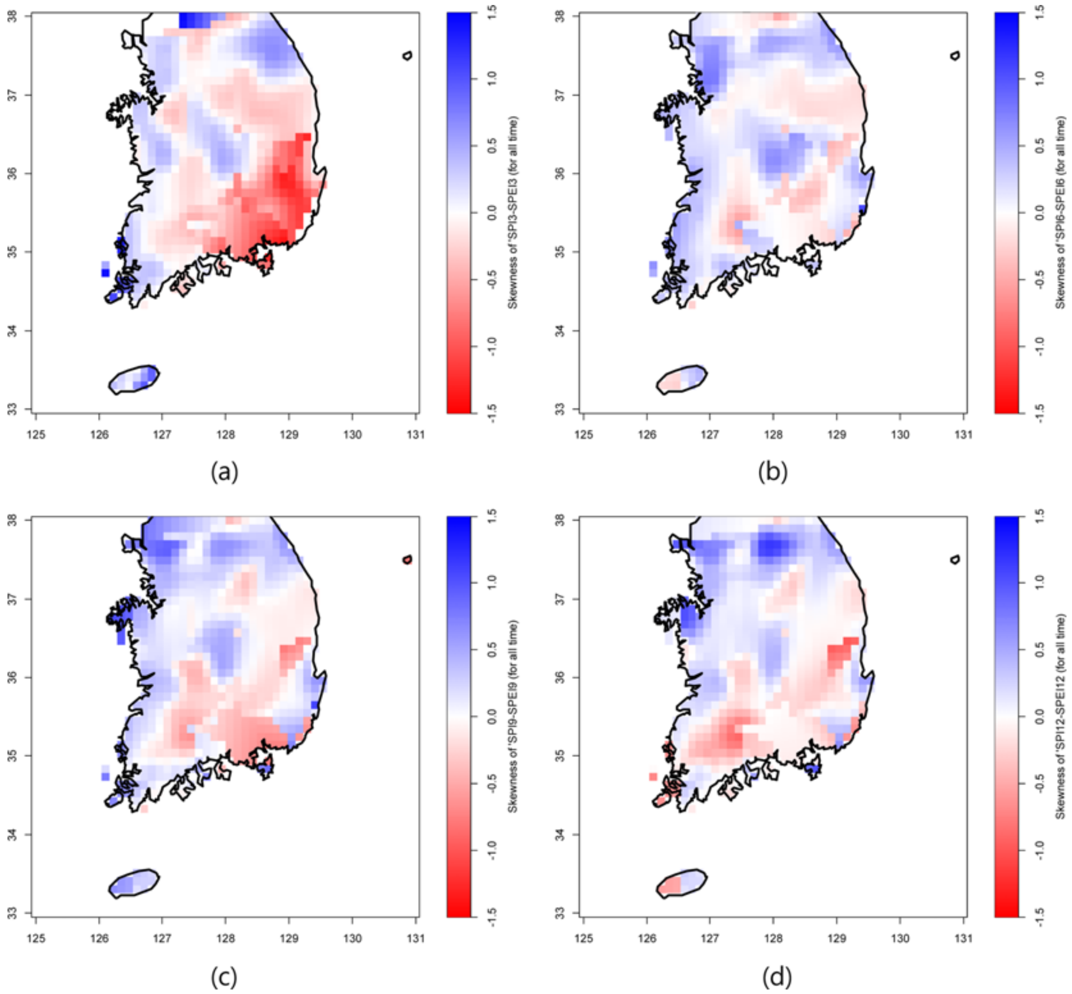

Fig. 3. Spatial Distribution of Skewness About the Difference of SPI and SPEI During 1973~2015 in South Korea for: (a) 3-month, (b) 6-month, (c) 9-month, (d) 12-month

and 0.1323. Regardless of drought occurrence, skewness increased with drought duration. For shorter durations, the severity of SPI became stronger than that of SPEI. In contrast, the severity of SPEI became stronger than that of SPI forlonger drought durations. Comparing theentire study period (Fig. 3) and the drought period (Fig. 4), the degree of skewness was much lower during the drought period. This shows that skewness decreases for severe droughts, and that SPI values were relatively higher than SPEI values. Furthermore, SPI droughts were found to be relatively more severe than SPEI droughts for shorter drought durations. These results indicate that shorter drought durations and more severe droughts lead to SPI values higher than SPEI values. These results, along with investigations of meteorological variables suggest that of the effects of low precipitation mainly were more visible under severe droughts with short durations but the effects decreased under moderate droughts with long durations.

4. Analysis of SPI and SPEI Based on Meteorological Variables

From Fig. 3 and 4, the following assumptions on the difference between SPI and SPEI could be made: the effect of precipitation on droughts is more for severe droughts with short durations (SPI induced more severe drought than SPEI). In this section, the difference between SPI and SPEI is compared with meteorological variables for validating the aforementioned assumptions. Details of an experiment on drought severity are presented in Tables 2 and 3, and those of another experiment on drought duration are presented in Table 4.

Drought severity related to SPI and SPEI was compared with spatially averaged meteorological variables such as precipitation, PET, temperature, wind speed, relative humidity, vapor pressure, and sunshine hour (Table 2-3). Tables 2 and 3 present changes in meteorological variables according to drought severity with SPI or SPEI values lower than -0.5 for a drought duration of 12 months. General threshold of drought for SPI and SPEI value is -1.0. However, in Table 2 and 3, range of -0.5 ~ 1.0 is added for investigating changes of meteorological variables more widely. According to Table 2, precipitation showed a steep decline and relative humidity and sunshine hour increased with higher SPI values. Changes in other variables such as PET, temperature, wind speed, and vapor pressure were not as significant. Decreases in

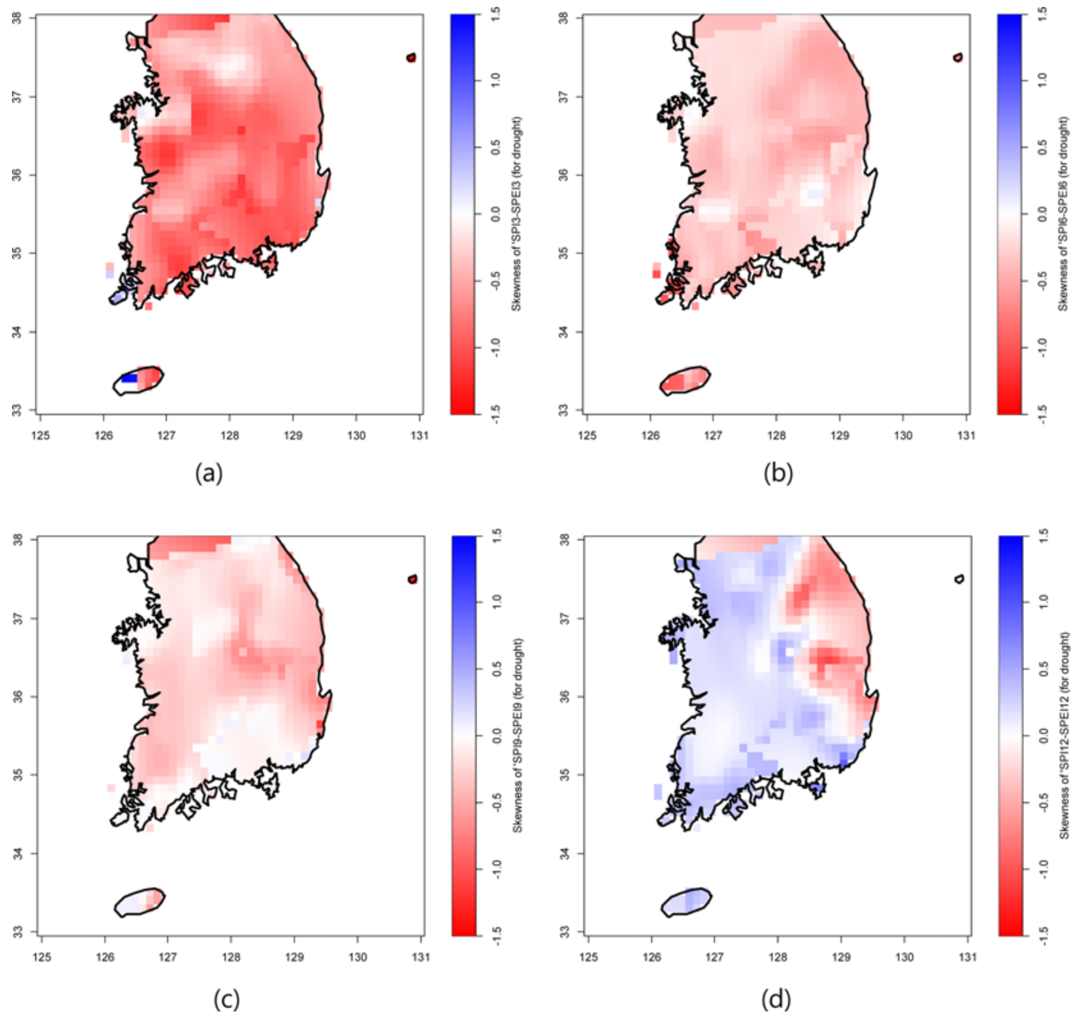

Fig. 4. Spatial Distribution of Skewness About the Difference of SPI and SPEI During Drought Period in 1973~2015 in South Korea for: (a) 3-month, (b) 6-month, (c) 9-month, (d) 12-month

Table 2. Meteorological Variables Under the SPI Drought Classification

If SPEI<-0.5	SPI > -0.5	-0.5 > SPI > -1.0	-1.0 > SPI > -1.5	-1.5 > SPI > -2.0	-2.0 > SPI
Precipitation (mm/yr)	1203.60	1112.48	998.77	902.27	811.38
PET (mm/yr)	1176.14	1125.16	1141.79	1156.49	1137.97
Temperature (¡É)	12.93	12.42	12.64	12.70	12.76
Wind speed (m/s)	2.07	2.10	2.08	2.14	2.13
Relative humidity (%)	67.72	69.58	69.12	69.06	71.07
Vapor pressure (hPa)	12.04	12.09	12.18	12.25	12.53
Sunshine hour (hr/yr)	2194.92	2344.07	2368.59	2420.73	2549.72

precipitation were related to increases in no-rain days and sunshine hour, and increases in relative humidity were attributed to increases in vapor in the air as a result of decreased precipitation. Table 3 shows changes in meteorological variables according to the severity of SPEI. Table 3 shows that precipitation dramatically decreased and sunshine hour increased. PET increased according to the definition of SPEI, and temperature increased and relative humidity decreased because of increased PET. The interpretations of the two tables were analyzed. In these two tables, there are two concurrences that precipitation decreased and sunshine hour increased for increasing severity of each drought index. According to strengthening severity of SPI and SPEI, precipitation showed the most prominent trend compared to other variables. Sunshine hour exhibited a relatively weak increasing trend and other meteorological variables showed different trends for different drought indices. In particular, relative humidity increased with increasing SPI values, but decreased with decreasing SPEI values. Different meteorological factors were found to have

Table 3. Meteorological Variables Under the SPEI Drought Classification

If SPI < -0.5	SPEI > -0.5	-0.5 > SPEI > -1.0	-1.0 > SPEI > -1.5	-1.5 > SPEI
Precipitation (mm/yr)	1142.45	1108.95	1006.95	909.82
PET (mm/yr)	1073.88	1126.73	1163.70	1180.01
Temperature (°C)	11.89	12.48	12.81	13.00
Wind speed (m/s)	2.14	2.09	2.09	2.14
Relative humidity (%)	71.55	69.66	67.96	69.12
Vapor pressure (hPa)	12.01	12.14	12.10	12.46
Sunshine hour (hr/yr)	2382.38	2337.33	2338.56	2419.32

Table 4. Ratios of Meteorological Variables Under Droughts Versus Entire Study Period for 3, 6, 9, and 12-month Duration

Ratio of drought-averaged per entire study period averaged (%)	Drought duration			
	3-month	6-month	9-month	12-month
Precipitation	-34.28	-25.74	-22.32	-20.32
PET	2.18	1.86	1.32	0.79
Temperature	-7.70	0.11	0.70	0.29
Wind speed	-0.02	-0.02	-0.05	0.08
Relative humidity	-2.34	-1.51	-0.79	-0.36
Vapor pressure	-3.09	-1.41	-0.58	-0.53
Sunshine hour	6.56	4.46	3.79	3.79

different effects on the drought indices.

Table 4 shows changes in meteorological variables indicating the occurrence or absence of drought for durations of 3, 6, 9, and 12 months regardless of drought indices. Droughts were defined by the severity of SPI or SPEI less than -0.5 for Table 4. Averaged meteorological variables during the drought period were divided by averaged meteorological variables during the entire study period. Changes in precipitation under the occurrence or absence of drought were more significant than other variables. When changes of precipitation were under -20%, changes of other variables varied within -10% ~ 10%. Only temperature (-7.70% for 3-month duration) and sunshine hour (6.56% for 3-month duration) had identifiable changes, but changes of other variables varied within -5% ~ 5%. For the analysis considering drought duration, magnitudes of changes decreased under increasing drought duration for all variables except wind speed. Changes of wind speed could be neglected because of tiny magnitude of changes which varied as -0.02% ~ 0.08%. The ratio of changes in precipitation sharply decreased from -34.28% to -20.32%, indicating that changes in precipitation had a dominant influence on the severity of droughts of short durations. However, this influence became significantly weak with increasing drought duration. With increased drought duration, the influences of other meteorological variables such as PET increased because of the weakened influence of precipitation.

5. Conclusions

In this study, we compared drought characteristics using two meteorological drought indices, SPI and SPEI. The effects of meteorological variables on droughts were analyzed using these indices. Severity was overestimated when SPI was used, and frequency and drought duration were overestimated when SPEI was used. Moreover, for severe droughts with short duration, the skewness of the difference between SPI and SPEI was negative, and low precipitation had a stronger influence on drought than other variables. Therefore, to investigate this, we compared SPI, SPEI, and meteorological variables, and the results showed that the high SPI and SPEI values were attributed to further decreased precipitation, but no significant trends were observed for other meteorological variables. Droughts of short duration were mainly affected by precipitation, but this influence weakened with increased drought duration.

We confirmed the following results on the basis of meteorological variables and a statistical analysis on the differences in SPI and SPEI. For severe or short–duration droughts, low precipitation is the main factor behind their occurrence; however, for weak or long–duration droughts, the importance of precipitation decreases, but the influence of other variables becomes stronger. Another important finding is the varying trends of other meteorological variables (except precipitation and sunshine hour) according to different drought indices. This implies the possibility of misunderstanding actual causes of droughts or misjudging the severity of droughts if only a single drought index is used.

It is difficult to measure hydrological droughts because records of observed runoff are limited and simulations of runoff involve large uncertainties in South Korea. For this reason, meteorological drought indices (especially SPI) for droughts of long durations can be sometimes substituted for hydrological drought indices. However, from the results of this study, the use of SPI for droughts of long duration as a replacement to hydrological drought indices is not suitable because the contribution of precipitation becomes extremely weak for long drought durations. In the future study, the combination of meteorological drought indices for detecting hydrological droughts will be analyzed, building on the major findings of this study.

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