Jour. Korean Earth Science Society, v. 27, no. 7, p. 804–815, December 2006

On the Characteristics of Meteorological Drought over the South Korea

Ill-Hee Yoon[1,*], Byung-Gil Lee[2] and Hee-Jong Kim[3]

[1]Department of Earth Science Education, Kyungpook National University, Daegu 702-701, Korea
[2]Jungdong High School, Daegu 701-835, Korea
[3]Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Daegu 702-701, Korea

Abstract: Meteorologists define a drought as a period of common dry weather. This may sound straightforward, but it is not so in reality. In this study, we attempted to identify meteorological drought conditions over South Korea. To evaluate the temporal and spatial variability of drought, we calculated two commonly used drought indices, the percent of normal precipitation (PNP) and the Palmer drought severity index (PDSI) calculated from fifty-eight meteorological stations below the Korean Meteorological Administration (KMA). The yearly precipitation has been growing gradually, and the amplitude between maximum and minimum also grow more explicitly from 1960's. According to the analysis of percentile anomaly of monthly precipitation, major drought duration was 1927~1929, 1937~1939, 1942~1944, 1967~1968, 1976~1977, 1982~1983, 1988, and 1994~1995. The severe drought occurred most frequently in Mokpo, Daegu, Jeonju, Busan, and Gangneung; it tended to occur more frequently in south sector than in mid sector of Korea and in south west sector than in south east sector. According to the analysis of seasonal distribution, extreme droughts occurred frequently in winter at Seoul, Gangneung, Jeonju, Daegu, and Busan. Severe droughts in summer were formed frequently at Seoul, Gangneung, and Mokpo, while that for spring at Jeonju, Daegu, and Busan. The results of PDSI distribution for the 1994~1995 drought period were one of the most severe and widely spreaded droughts; it occurred most frequently in the south sector of South Korea. The comparison of time series between PDSI and Normal Percent showed that they exhibit a strong compatibility for the entire study period; it implies that both drought indices are useful method to indicate drought severity.

Keywords: meteorological drought, Drought Index, PDSI, Normal Percent, extreme drought

Introduction

Drought is not merely a phenomenon indicating a lack of rainfall. Drought is a persistent moisture deficiency below long-term average conditions that, on average, balance precipitation and evapotranspiration in a given area (Collier and Webb, 2002). Meteorological drought is defined as a period of unusually dry weather. This sounds straightforward, but it is not that simple. “Unusually” means the frequency of more than two weeks without rain (Allaby, 2003). A meteorologic drought can be measured in terms of the amount of falling rain and the amount of moisture retained in the soil. Palmer (1965) attempted to bring some order into the situation by devising a way to classify meteorological droughts and periods of wet weather by means of a scale from extremely wet to extremely drought.

As soon as it begins to affect farm crops, a meteorological drought becomes an agricultural drought. This happens when the soil moisture is insufficient to meet immediate requirements for crops growth (Allaby, 2003). However, drought can also be defined as a unique phenomenon beyond the meteorologist's measurements. Hydrological drought occurs when surface water supplies steadily diminish during a dry spell. Ecological drought is detrimental to native plants without the benefit of irrigation (Collier and Webb, 2002). When a drought begins to affect the supply of goods and services to a community, it becomes a socioeconomical drought (Allaby, 2003).

Among researches conducted on national and international drought control and drought index, Ahn et al. (1988) analysed 6 regions by defining Agricultural

*Corresponding author: ihyoon@knu.ac.kr
Tel: 82-53-950-5922
Fax: 82-53-950-5946

Drought Index (ANI) with drought intensity and duration to examine agricultural droughts. Cho et al. (1998) developed a drought prediction and warning index calculation method. These authors also applied it to the establishment of water supply plans according to drought severity degrees using Phillips Drought Index (PDI) in urban areas. Palmer (1965) defined drought as 'abnormal lack of water for a long period' and developed Palmer Drought Severity Index (PDSI) by analysing monthly water balance in soil with the amount of precipitation, transpiration and evaporation. PDSI is popular and has been widely used to monitor drought in many areas including the northern part of the United States. Its application has also been made to diverse periods and areas (Rao and Padmanabhan, 1982; Karl, 1983).

In Korea, Meteorological Research Institute (METRI) compared the atmospheric circulation of a droughty year and that of a normal year by applying PDSI to 25 observation points for 30 years from the year 1961 to 1990 (Meteorological Research Institute). Ahn (1996) and Yoon et al. (1997) analysed chief droughty periods of the past by applying PDSI to 68 points all over the nation, after complementing climatic feature factors and drought index estimation with Korean data. These researches did not give a full detail of climatic characteristics. Byun and Wilhite (1999) studied daily drought index that can be used to predict spring drought. However, the index did not contain the general function.

In this paper, we discussed several limitations of the PDSI. McKee et al. (1995) suggested that the PDSI is designed for agriculture; it is however found that such index is not accurate enough represent the hydrological impacts resulting from droughts of long time scale. Kogan (1995) showed that the PDSI, which being applied within the United States, has little acceptance elsewhere.

Since 1960, major periods of drought have been observed as the serious drought in Honam and Yeongnam regions (1967~1968, 1994~1995), and part of Yeongnam region (1976~1977, 1981~1982, 1987~1988). Since 1900, about 10-year drought cycle tends to be shorter gradually into a 5~6 year cycle. Such phenomenon is frequently observed in the southern part of the Korean peninsula.

This study examines both drought cycles and seasonal and regional drought distributions over South Korea by a statistical analysis of precipitation changes. It also investigates regional characteristics of drought in the southern part with Palmer Drought Severity Index (PDSI).

Palmer Drought Severity Index (PDSI)

Palmer (1965) selected Kansas in the West and Iowa in the Middle West in order to develop an index capable of making temporal and spacial comparisons of drought statistics. Everyday weather that people feel in semiarid Kansas may differ from that in subhumid Iowa and in consideration of these climatic deviations, he created a drought index that can be used for the comparison with other regions.

Palmer Drought Severity Index calculates the difference between adequate precipitation and actual precipitation on the monthly basis by using Thornthwaite's water balance method (Thornthwaite and Mather, 1957) and draws a drought index with regional features taken into account.

Palmer drought severity index (Palmer, 1965) is approximated by

$$X_i = \sum_{i=1}^{i} \frac{z_i}{(0.309t + 2.691)} \tag{1}$$

where X_i is monthly PDSI, z_i monthly moisture anomaly index and t duration of drought. The moisture anomaly represents with respect to the current season and the local climate.

In order to evaluate the contribution of each month, we can set $i=1$ and $t=1$ in equation (1) and we have,

$$X_i = \frac{z_i}{3} \tag{2}$$

Since this is an initial month,

$$X_1 - X_0 = \Delta X_1 = \frac{z_i}{3} \quad (3)$$

From equation (1), it is apparent that Σz must increase as t increases in order to maintain a given value of X. The rate of increase of t is constant; i.e., t increases by 1 each month, thereby increasing the denominator by steps of 0.309. Therefore, the rate at which the index, z, must increase in order to maintain a constant value of $X(\Delta X = 0)$ depends on the value of X that is to be maintained. This reasoning suggests that for all months following an initial dry month an additional term must be added to equation (3) and that the equation is of the form,

$$\Delta X_1 = \frac{z_i}{3} + cX_{i-1} \quad (4)$$

where, $\Delta X_1 = X_i - X_{i-1}$

If we place these values of z_1, X_{i-1}, and ΔX into equation (4), we have c value (−0.103) and the final equation is:

$$\Delta X_1 = \frac{z_i}{3} - 0.103X_{i-1} \quad (5)$$

This equation can be used to compute the monthly contributions to drought severity. Of course, the sum of the increments gives the severity itself, i.e.,

$$\Delta X_1 = X_{i-1} + \frac{z_i}{3} - 0.103X_{i-1} \quad (6)$$

Palmer (1965) defined the extent of humid season and dry season according to drought indices as Table 1.

Table 1. Palmer drought indices

X	Class
4.00	Extreme wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient drought
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
-4.00	Extreme drought

Estimation of Drought Index

Yearly changes of the average annual precipitation

Fig. 1 shows yearly changes in the national average of annual precipitation since the first meteorological observation in 1904. From the year 1950 on, the annual precipitation has been on the rise and its fluctuation scope also tends to increase.

Since 1904 the periods of successive below average rainfall all over the nation are 1927~1929, 1937~1939, 1942~1944, 1967~1968, 1976~1977, 1982~1983, 1988, and 1994~1995. Among those periods, 1939, 1968, 1978 and 1982 suffered very severe drought. In the year 1939, the national average of annual precipitation was only 689.2 mm, the least amount of

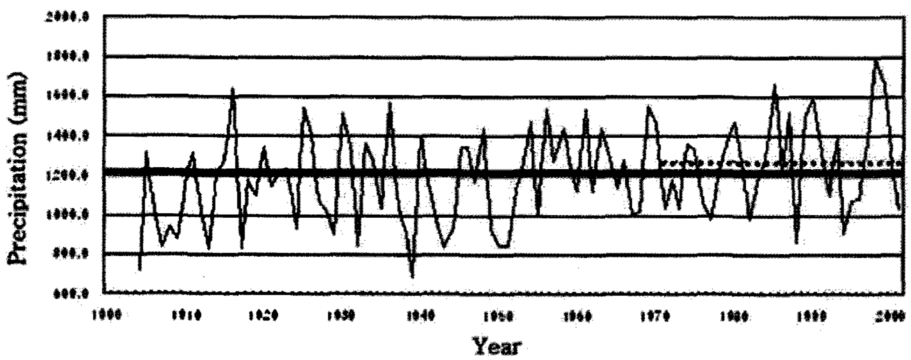


Fig. 1. Time series of annual precipitation of South Korea from 1904 to 2001. Solid line (Nationwide), Bold line (Centennial average), Dot line (Recent 3 Decade Average).

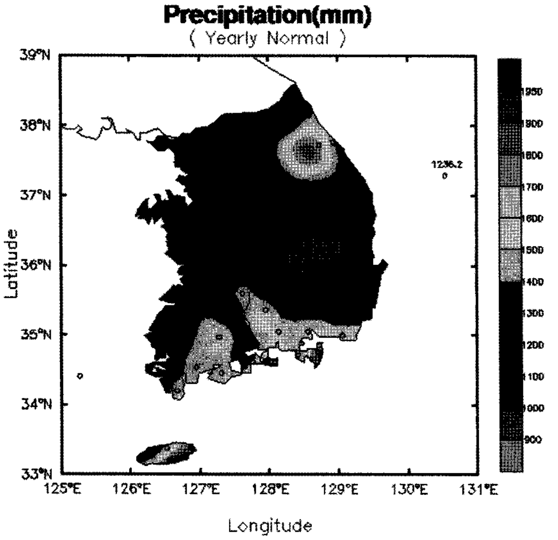


Fig. 2. Yearly normal precipitation of South Korea during 1971~2000 (Korea Meteorological Administration).

rainfall since the first meteorological observation.

Fig. 2 shows distribution chart of the average year precipitation made by Korea Meteorological Administration. As climatological drought is defined as a phenomenon of present lack of precipitation compared with that of the average year, the region with less precipitation in climatological terms might have a high probability that temporary insufficient rainfall due to meteorological factors turns into drought. Therefore, the national distribution of the normal year precipitation is necessary to estimate areas which will undergo drought frequently.

According to the data from Korea Meteorological Administration, the annual precipitation of Kyeongbuk inland areas such as Andong, Daegu, Yeongdeok, Uiseong, Gumi and Yeongcheon is below 1,050 mm, about 200 mm lower than the average national precipitation. Especially, the annual precipitation of Uiseong area is the lowest in Korea as just 972.1 mm. In addition, Mokpo, Inje, Chupungnyeong, and Uljin areas record slightly over 1,100 mm annual precipitation.

Average year percentage

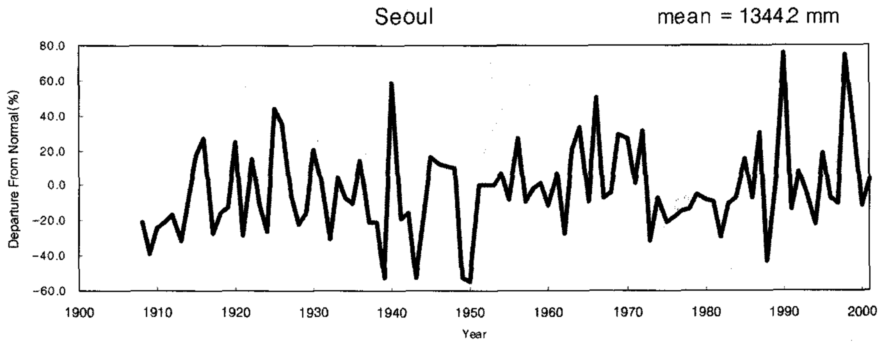
The differences from the average year annual precipitation from the year 1971 to 2000 in chief points are shown in terms of percentage from Fig. 3(a) to Fig. 3(f).

The observation period past the year 1990 seems to satisfy normal distribution as a whole. Seoul and Busan recorded a humid year 4 times when the precipitation was over 45% more than the average year value. Seoul suffered severe drought 4 times when the precipitation was over 45% below the average year value and Mokpo 3 times. As Daegu and Mokpo recorded 16 and 19 times respectively the droughty year when the precipitation was over 25% less than the average year annual precipitation, the probability of drought due to the accumulated water shortage is extremely high (Table 2).

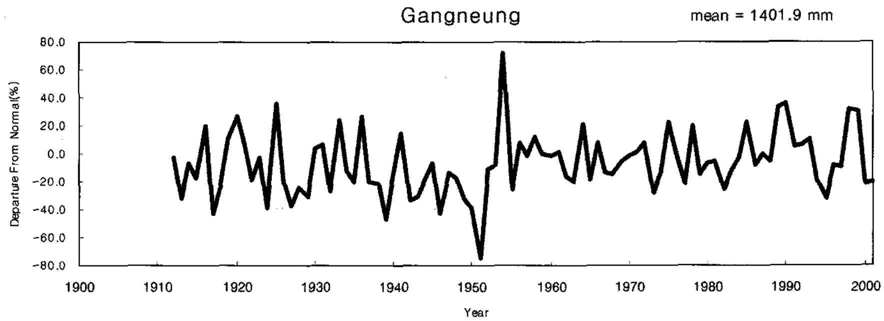
In comparison with that of the central area, relative drought frequency of the southern area is analysed with 58 observation points in Fig. 4. Here, frequency 1 means the annual precipitation measured in one observation point.

Among 2,337 cases, the year experiencing mild drought with 10~25% below the average year annual precipitation is 215 of 900 times (24%) in the central area and 334 of 1,437 times (23%) in the southern area. The central area suffered mild drought slightly more than the southern area. The year with severe drought with 25-45% less than the average annual precipitation is 116 times (13%) in the central area and 214 times (15%) in the southern area, 2% over the rate of the central area. The year with extreme drought with 45 % less than the average annual precipitation is 43 times (3%) in the southern area, more often than the central area of 14 times (2%).

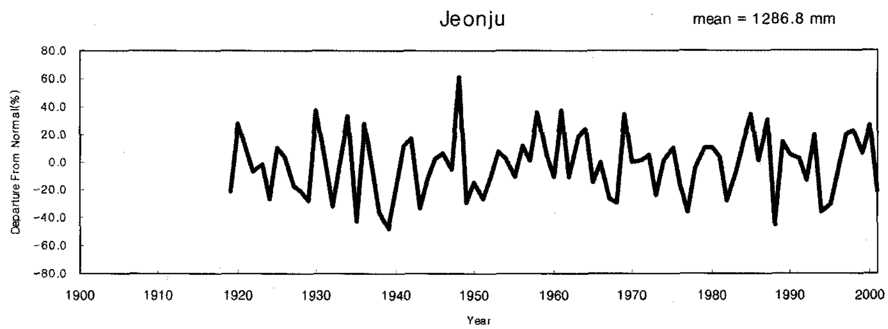
The year suffering mild drought with 10~25% less than the average year annual precipitation is 211 (25%) of 828 times in the south-eastern area and 123 (20%) of 609 times in the south-western area. The incidence of drought in the south-eastern area is relatively higher than in the south-western part. But the year with severe drought when the annual precipitation was 25~45% lower than the average year rate is 107 times (13%) in the south-eastern area and 107 times (18%) in the south-western area, 5% more



(a)



(b)

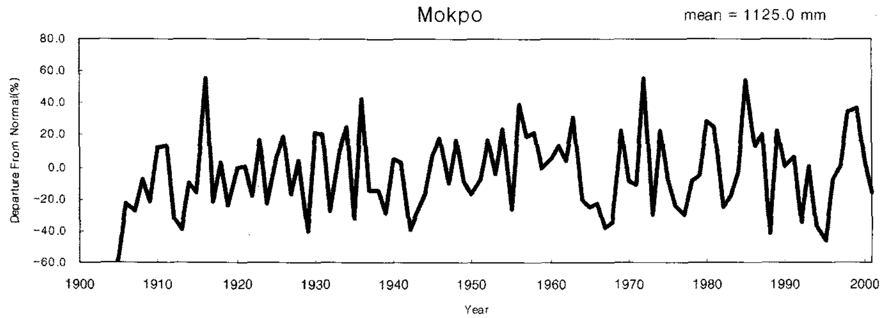


(c)

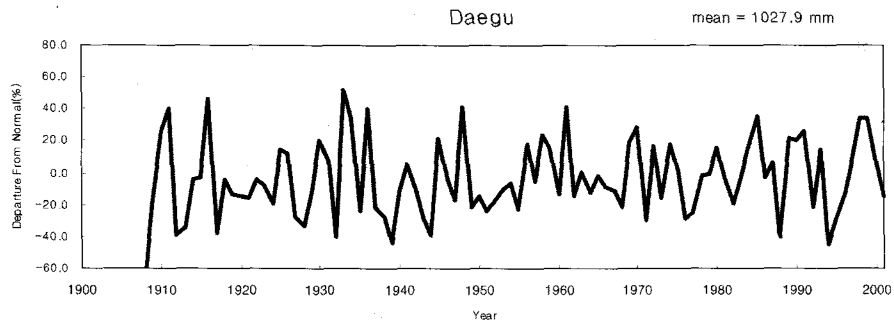
Fig. 3. Time series of annual precipitation as a percentile departure from normal value for (a) Seoul, (b) Gangneung, (c) Jeonju, (d) Mokpo, (e) Daegu, and (f) Busan.

than the south-eastern area. The year with extreme drought, 45% less than the average, is the same rate in both areas, 23 times (3%) in the south-eastern area and 20 times (3%) in the south-western area.

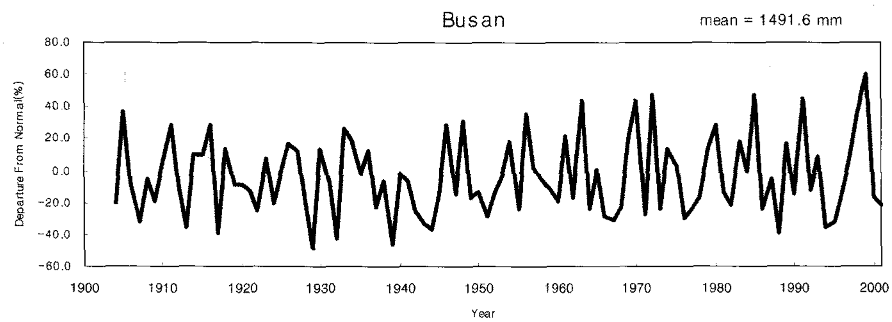
Six sites, two of each region, are selected for the analysis of seasonal factors. The frequency of drought from the first observation day to the year 2001 is analysed and the findings are displayed in Table 3. Seasonal deviation is extremely great and regional features are also different. When every site is compared with each other in the average rate of annual precipitation in terms of seasons, Daegu and



(d)



(e)



(f)

Fig. 3. Continued.

Mokpo have relatively low yearly rainfall and suffer frequent drought, as shown in Fig. 5.

In Seoul, Gangneung and Mokpo, severe drought (–45~–25) happens mostly in summer, while in Jeonju, Daegu and Busan, it did mostly in spring. Extreme humidity also occurs most frequently in winter as drought does. In Seoul, Gangneung, Jeonju, Daegu and Busan area, extreme drought happens most often in winter, but Mokpo suffers it frequently in autumn.

In most areas, over 70% of annual precipitation occurs in summer but about 10% level of summer rainfall happens in winter, so drought aspects tend to be exaggerated in index. Therefore, it is necessary to develop a new drought index including not only precipitation but also dry days for the expression of wintry drought level.

Table 2. Frequency of drought of six sites during 1904~2001

	Seoul	Gangneung	Jeonju	Mokpo	Daegu	Busan
>45	4	1	1	3	2	4
25 to 45	10	7	10	8	11	11
10 to 25	11	10	15	18	15	14
-10 to 10	28	29	26	29	22	22
-25 to -10	24	27	15	18	27	31
-45 to -25	9	14	14	19	16	14
-45	4	2	2	3	1	2
Observation period (year)	91	90	83	98	94	98

Variation of PDSI

Palmer Drought Severity Index (PDSI) in six points estimated on the basis of monthly rainfall data and average monthly temperature from the first observation day to the year 2001 is expressed in Fig. 6 through Fig. 8. In general, the percentage and time series of the average year annual precipitation match well. It is because drought index expresses accumulated results of lack or excess of actual rainfall compared with the given climatic values. For the sake of convenience, it is expressed by 50-year division as a unit and two sites are overlapped.

In Seoul, drought periods during the observation period are 1938~1941, 1943~1946, 1946~1949, 1988~1990, and 1993~1994, and humid periods 1926~1928, 1946~1949, 1990~1992, and 1998~2000. The distinction between drought and humid periods is clear. Gangneung shows less fluctuation in index than Seoul, but tends to suffer worse drought in the dry season as severe drought with below −2 in index occurs frequently.

Jeonju and Mokpo are 100 km apart geographically but has similar topographical features as the two cities are located on flat land in the south-western coastal area. So, time series of their dry and humid periods almost agree with each other. Chief drought periods are 1929, 1939~1941, 1967~1968, 1977~1979, 1988, and 1993~1996.

In Daegu and Busan, dry and humid periods happen at almost the same time, but in the given period, the severity of drought and humidity is greater in Daegu than in Busan. This is because the average annual precipitation in Daegu is 1027.9 mm, 463.7 mm lower

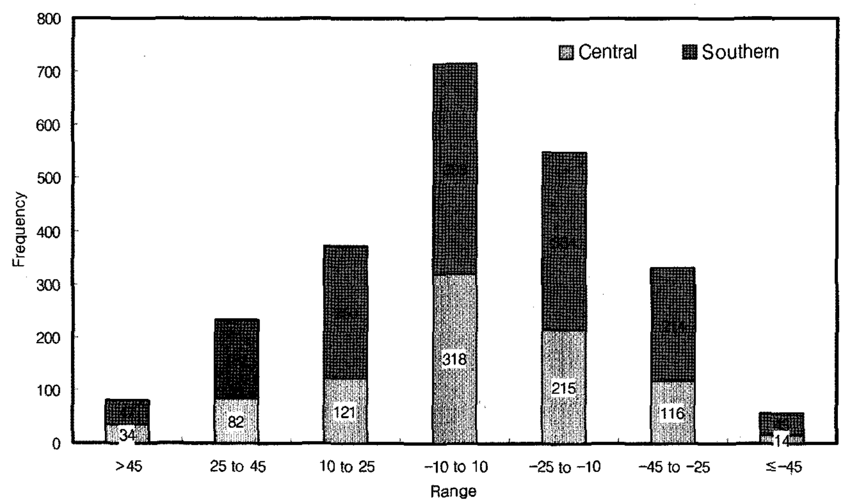


Fig. 4. Comparison of drought frequency in the southern area and the central area of South Korea during 1904~2001

Table 3. Distribution of seasonal precipitation of six cities

Classification		>45		25 to 45		10 to 25		-10 to 10		-25 to -10		-45 to -25		<-45		Total	
		Freq-uency	%	Freq-uency	%	Freq-uency	%	Freq-uency	%	Freq-uency	%	Freq-uency	%	Freq-uency	%	Freq-uency	%
Seoul	Spring	10	11.0	8	8.8	10	11.0	13	14.3	21	23.1	15	16.5	14	15.4	91	100
	Summer	9	9.9	9	9.9	7	7.7	24	26.4	16	17.6	21	23.1	5	5.5	91	100
	Autumn	13	14.3	9	9.9	7	7.7	17	18.7	10	11.0	18	19.8	17	18.7	91	100
	Winter	17	18.3	11	11.8	8	8.6	8	8.6	18	19.4	12	12.9	19	20.4	93	100
	Mean	12	13	9	10	8	9	16	17	16	18	17	18	14	15	92	100
Gang-nueng	Spring	5	5.6	8	9.0	15	16.9	18	20.2	15	16.9	10	11.2	18	20.2	89	100
	Summer	6	6.7	9	10.1	7	7.9	24	27.0	16	18.0	18	20.2	9	10.1	89	100
	Autumn	11	12.1	13	14.3	6	6.6	11	12.1	14	15.4	18	19.8	18	19.8	91	100
	Winter	16	18.0	7	7.9	8	9.0	10	11.2	8	9.0	16	18.0	24	27.0	89	100
	Mean	10	11	9	10	9	10	16	18	13	15	16	17	17	19	90	100
Jeonju	Spring	8	9.6	8	9.6	10	12.0	14	16.9	17	20.5	20	24.1	6	7.2	83	100
	Summer	8	9.5	9	10.7	7	8.3	21	25.0	17	20.2	15	17.9	7	8.3	84	100
	Autumn	11	13.1	10	11.9	6	7.1	19	22.6	17	20.2	10	11.9	11	13.1	84	100
	Winter	11	13.1	9	10.7	8	9.5	15	17.9	15	17.9	12	14.3	14	16.7	84	100
	Mean	10	11	9	11	8	9	17	21	17	20	14	17	10	11	84	100
Mokpo	Spring	9	9.2	16	16.3	9	9.2	27	27.6	11	11.2	15	15.3	11	11.2	98	100
	Summer	10	10.2	6	6.1	13	13.3	21	21.4	10	10.2	24	24.5	14	14.3	98	100
	Autumn	15	15.3	10	10.2	13	13.3	12	12.2	13	13.3	20	20.4	15	15.3	98	100
	Winter	14	14.4	10	10.3	14	14.4	18	18.6	19	19.6	12	12.4	10	10.3	97	100
	Mean	12	12	11	11	12	13	20	20	13	14	18	18	13	13	98	100
Daegu	Spring	8	8.4	7	7.4	11	11.6	22	23.2	17	17.9	18	18.9	12	12.6	95	100
	Summer	8	8.4	14	14.7	6	6.3	21	22.1	17	17.9	15	15.8	14	14.7	95	100
	Autumn	17	17.9	10	10.5	15	15.8	14	14.7	11	11.6	13	13.7	15	15.8	95	100
	Winter	18	19.1	12	12.8	7	7.4	12	12.8	13	13.8	14	14.9	18	19.1	94	100
	Mean	13	13	11	11	10	10	17	18	15	15	15	16	15	16	95	100
Busan	Spring	6	6.1	10	10.2	12	12.2	19	19.4	20	20.4	21	21.4	10	10.2	98	100
	Summer	7	7.1	13	13.3	14	14.3	21	21.4	9	9.2	17	17.3	17	17.3	98	100
	Autumn	23	23.5	5	5.1	7	7.1	16	16.3	16	16.3	15	15.3	16	16.3	98	100
	Winter	20	20.4	8	8.2	5	5.1	9	9.2	20	20.4	15	15.3	21	21.4	98	100
	Mean	14	14	9	9	10	10	16	17	16	17	17	17	16	16	98	100

than in Busan with the average annual precipitation of 1491.6 mm.

Fig. 9 shows time series of PDSI and the average year precipitation percentage from the 1955 to 2001 in Daegu area. Time series of precipitation calculates annual precipitation by percentage differences in climatic values, and PDSI matches ideally well with the average year percentage. The finding is the same with the previous research which compared them on the basis of monthly precipitation and suggests that annual precipitation can be used as a significant factor in estimating drought index.

Summary and Conclusion

From 1904 to 2001, using precipitation data, we studied variations of PDSI and regional characteristics of PDSI over South Korea. The results are summarized as followed:

1) The year recording 25% less rainfall than the average year annual precipitation happen 21 times in Mokpo, 17 times in Daegu, and 16 times in Jeonju, Busan, and Gangneung, so it is estimated that these areas suffer drought frequently. Regionally, the central part of the country recorded 116 times of drought (13

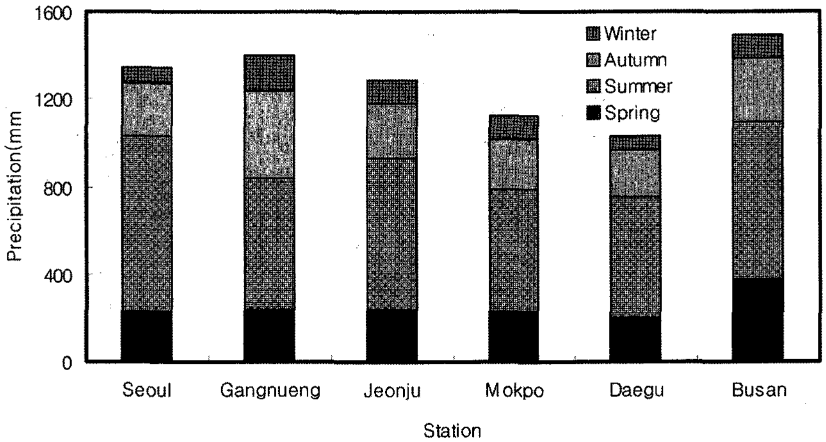


Fig. 5. Seasonal distribution of the average annual precipitation for six cities.

%) and the southern part 214 times (15%), 2% higher in drought frequency than the former.

2) Severe drought 25~45% lower than the average annual precipitation occurs more often in the south-western area than in the south-eastern area. Extreme drought 45% less than the average happens at almost the same rate in the two areas.

3) Seasonal drought frequency analysis indicates that extreme drought 45% less than the average annual precipitation happens mostly in winter in Seoul, Gangneung, Jeonju, Daegu and Busan but in Mokpo it happens chiefly in autumn. Severe drought 25~45% lower than the average precipitation happens most often in summer in Seoul, Gangneung and Mokpo but in Jeonju, Daegu and Busan, it occurs mostly in spring.

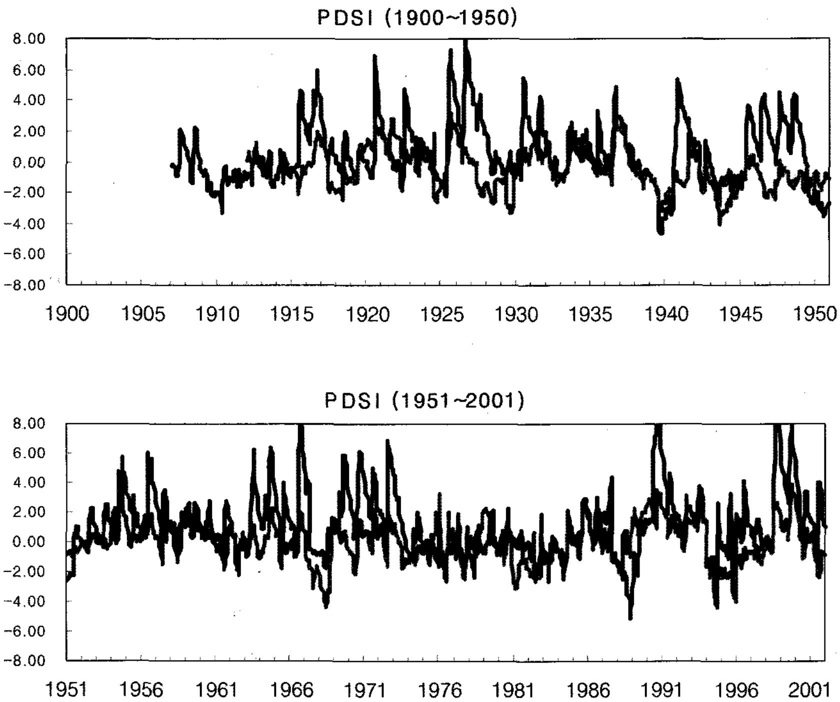


Fig. 6. Time series of palmer drought severity index at Seoul (black) and Gangneung (gray).

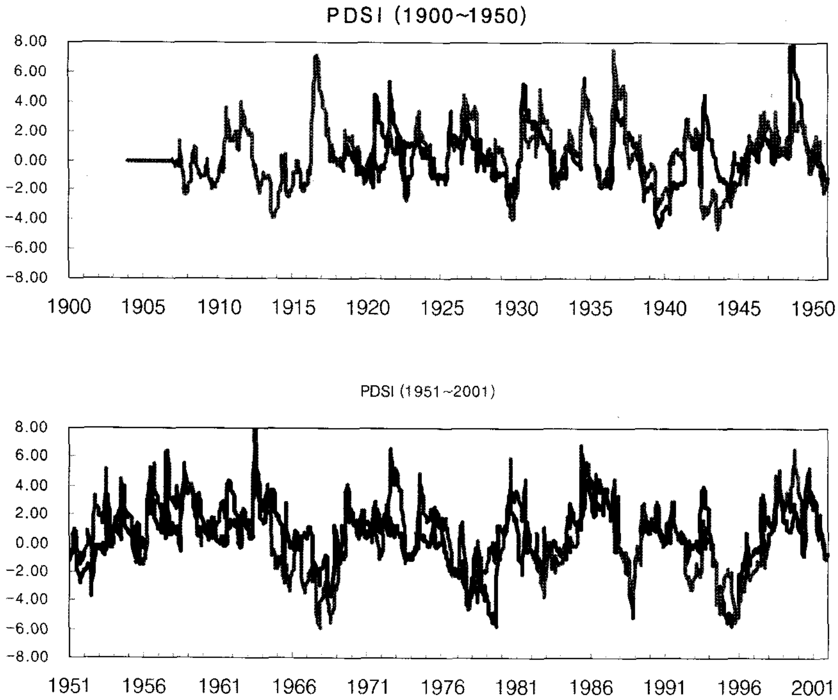


Fig. 7. Same as Fig. 6, but Jeonju (black) and Mokpo (gray).

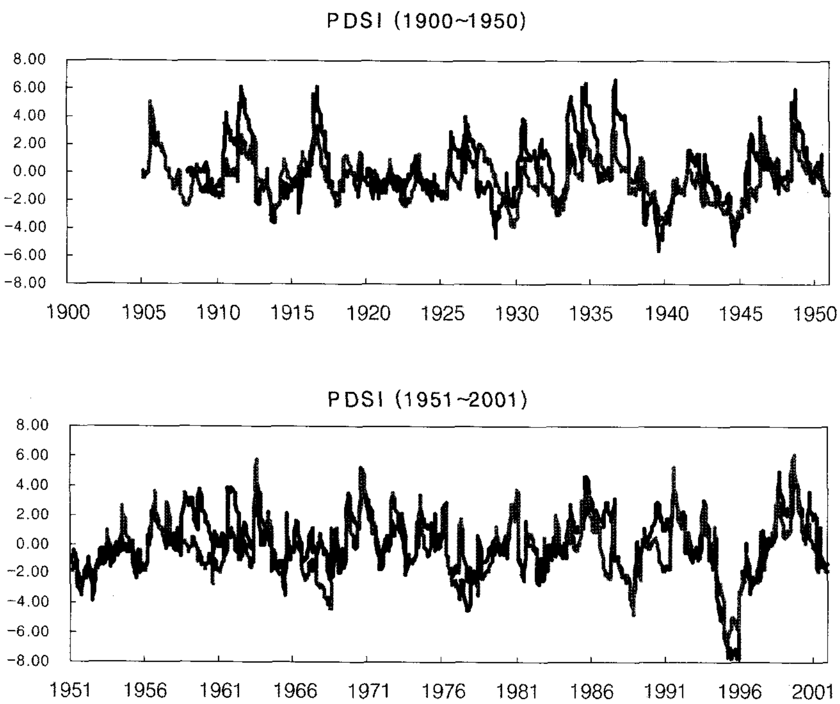


Fig. 8. Same as Fig. 6, but Daegu (black) and Busan (gray).

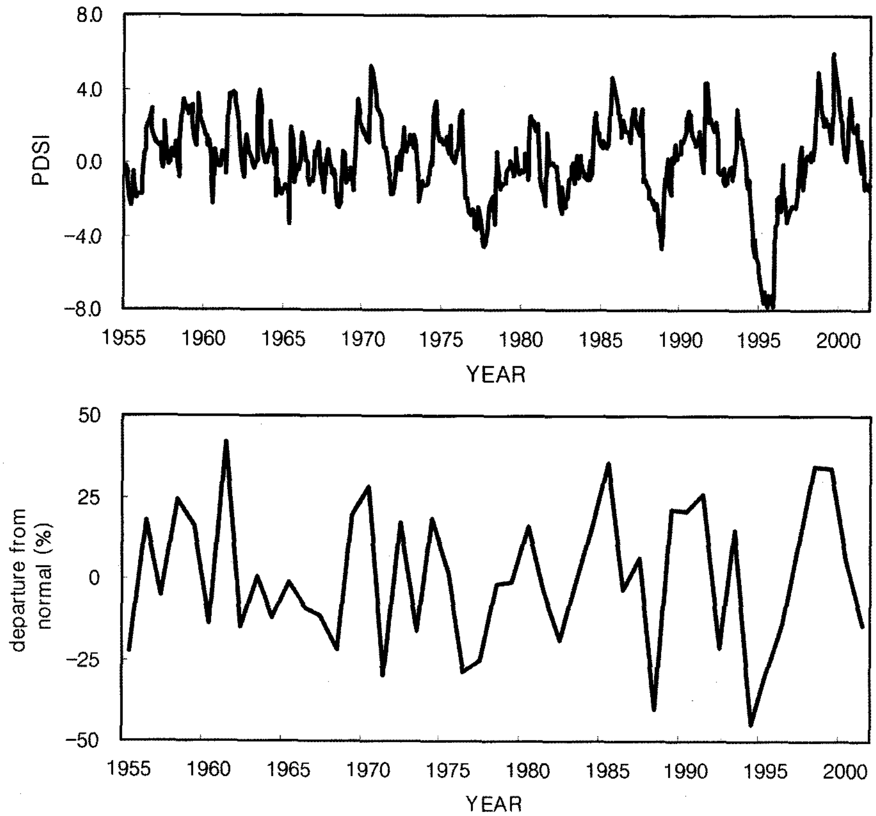


Fig. 9. Comparison of Annual Precipitation and Palmer Drought Severity Index at Daegu during 1955~2001.

4) The analysis of monthly PDSI in Gangneung, Daegu, Jeonju, and Busan area since the first observation day to the year 2001 makes it clear that drought in the southern part of the nation such as Daegu, Jeonju, Busan and Mokpo from 1994 to 1995 was the severest.

5) The comparison of PDSI and time series of the average year annual precipitation percentage in Daegu from the year 1955 to 2001 shows a tendency to agree in most sections.

6) Increasing analysis site and analyzing regional characteristics, it could be not only expected regional property of drought but forecast of drought.

Acknowledgment

This research was supported by Kyungpook National University Research Fund, 2003. We thanks Kyungpook National University for its financial support.

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Manuscript received: 2 September 2006
Revised manuscript received: 10 November 2006
Manuscript accepted: 11 November 2006