AUGUST RAINFALL IN KOREA AND ITS ASSOCIATION WITH CIRCULATIONS

KYUNG-JA HA[†]

Division of Earth Environmental System, Pusan National University, Busan 609-735, Korea

KYUNG-SOOK YUN

Division of Earth Environmental System, Pusan National University, Busan 609-735, Korea

The recent characteristics of the summer rainfall in Korea have shown a significant change from the climatological features. In the present study, the changes in the Changma (July rainfall) and post-Changma (August rainfall) over the Korean Peninsula have been investigated using a long-term record based on the synoptic station data that includes Seoul, Busan, Daegu, Mokpo, and Gangneung. The association between the large-scale circulation and the changes in the rainfall has also been examined. The August rainfall has increased with time, while the July rainfall has not changed. The July rainfall has impacts of regional ocean variability, and the August rainfall has impacts of remote ocean variability on intensity, including the Indian Ocean and the tropical eastern Pacific. The August rainfall is strongly associated with the westward extension of the western North Pacific (WNP) high and position of the Bonin high. The August rainfall exhibits the extratropical Eurasian wave-like structure with a steady response during the summertime (June to August), while the July rainfall is closely related to the southwesterly monsoon flow during that month. Consequently, the August rainfall exhibits a clearer association with remote Ocean variability and large-scale circulation.

1. Introduction

The summer monsoon rainfall in Korea is called Changma and its precipitation concentrated to July. However, the characteristics of summer rainfall in Korea have changed in the last half-century (e.g., Ho *et al.*, 2003[7], Wang *et al.*, 2007[14], and Kwon *et al.*, 2007[9]). In particular, the August rainfall has increased considerably (Cha *et al.*, 2007[2]). Ha and Ha (2006)[4] have also noted the increase of the "August mode" from the EOF analysis. The abrupt change in summer rainfall causes huge damage to human activities and property.

Although most prior studies have focused on the summertime (i.e., June-

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[†] Corresponding author: kjha@pusan.ac.kr

July-August), the rainfall in July and August has remarkably distinctive characteristics in their interannual variability (Cha *et al.*, 2007[2]). For example, the July rainfall is mainly affected by the East Asian summer monsoon front (Ha *et al.*, 2005[6]), while the August rainfall is modulated by complex atmospheric mechanisms (i.e., direct and indirect effects of typhoons, mesoscale complex systems, and thunderstorms). To understand the climate changes in the Korean summer rainfall, the similarities and discrepancies in the interannual variability of July and August rainfall should be investigated first. To do so, the changes in Changma (July rainfall) and Post-Changma (August rainfall) over the Korean Peninsula have been discussed, using long-term records based on the synoptic station data including those of Seoul, Busan, Daegu, Mokpo, and Gangneung. Furthermore, the characteristics of the sea surface temperature (SST) and circulation associated with the July/August rainfall anomalies are investigated in the present study.

2. Data and Method

2.1. *Data*

To ameliorate the long-term variability in Korean rainfall, we used the precipitation dataset obtained by the Korean Meteorological Administration (KMA) from 1912 to 2006. Five synoptic stations that made consistent observations from 1912 to the present were selected for this analysis. The five stations are represented in Table 1.

Table 1. The five synoptic stations selected in this study.

	Longitude (°E)	Latitude (°N)	Altitude (m)
Seoul	126.96	37.56	85.50
Busan	129.03	35.10	69.23
Daegu	128.62	35.87	57.64
Mokpo	126.38	34.80	37.88
Gangneung	128.88	37.73	25.91

Composite and regression analyses for the circulations are carried out to find the association with a large-scale environment using the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data from 1948 to 2006 (59-years). The regression to the SST (obtained from HadISST) from the rainfall projection was obtained to investigate the spatial correlation distributions for the interested area.

2.2. *Methodology*

First, we try to detect the detection of climatic changes over the long-term record. We used the Pettitt (1980)[13] test, which is a change detection method in the median of the sequence of observation and a stout test of the change point resistant to outliers. Pettitt (1980)[13] derived the test statistics on whether there is change in the median of the sequence of observation on the basis of the rank of the observations. The Pettitt test uses a remarkably stable distribution and provides a reliable estimation of the change point resistant to outliers.

The Pettitt test procedure is as follows: First, the observations (X) are ranked from 1 to N (i.e., $X_1, \ldots, X_N$). Suppose R_i is the rank associated with the observation X_i , so we can calculate the sum of the ranks of the observations at each place (i.e., j) in the series as described below.

$$W_j = \sum_{i=1}^{j} R_i, \qquad j = 1,\ 2, \ldots, N-1 \tag{1}$$

Then it is easier to rewrite U_j as a rank statistic.

$$U_j = 2W_j - j(N+1) \qquad j = 1,\ 2, \ldots, N-1 \tag{2}$$

The value of j where the maximum in the absolute value of U_j occurs (that is, $K_{m,n}$) is the estimated change point in the sequence and is denoted by m ($n = N - m$).

Now we conduct a statistical test to see whether the estimated change point m is significant using the sampling distribution of W_m . Thus, the significance probabilities associated with the value m are approximately given by

$$P = 2\exp\left\{-6W_m^2/(N^3 + N^2)\right\} \tag{3}$$

The detailed extent is described by Pettitt (1979)[12]. The Pettitt test (Ha and Ha, 2006[4]) was applied for the detection of precipitation. For the July and August precipitation averaged over the five stations, the Pettitt test was performed with a significance level of 0.01. One significant change point was found in 1967 (1953) on the August (July) rainfall, respectively.

3. The climate change in July/August rainfall

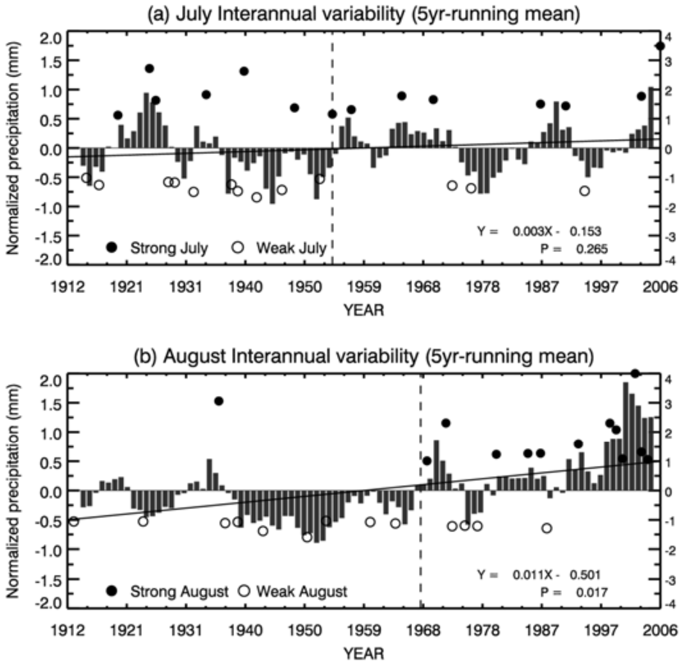


Figure 1. Interannual variability of 5yr-running averaged (a) July and (b) August rainfall. The closed (open) circles indicate the rainfall that the normalized value is greater than 1.0 (less than -1.0) standard deviation (right axis), and the perpendicular dashed line denotes the change point of July/August rainfall. (a)-(b) The solid line indicates the linear trend of the series.

To investigate the long-term variability of the rainfall, the interannual variability of 5-year running averaged rainfall for July and August is compared as shown in Figs. 1a and 1b. While the July rainfall does not show any significant change trend, the August rainfall displays a clear increasing trend after late 1960s. This upward trend significant at the 95% confidence level (i.e., $P < 0.05$) can be shown in the result from Mann-Kendall test (Mann, 1945[10]; Kendall, 1975[8]). The rainfall change in August is especially obvious after the change point (that is, 1967). To locate the details of this change, extreme July and August rainfall years are displayed. The strong (weak) years are defined as having the rainfall anomalies greater than 1.0 (less than -1.0) standard deviation of normalized values, respectively for July and August. For July rainfall, the variability before the change point is somewhat larger than that after the change point (i.e., 1953). The numbers of the strong and weak years before the change point are approximately twice as many as that after the change point. This indicates that the July rainfall has had a relatively small fluctuation in recent years. On the other hand, the August rainfall exhibits distinct characteristics before and after its change point. Most of the strong August rainfall events occurred after 1967, while many weak August rainfall years appear before 1967.

Table 2. Statistics for the July and August precipitation before and after Pettitt's change point.

	Period	N	Mean	Median	SD
July	1912-1953	42	242.2	229.8	124.3
	1954-2006	53	270.8	260.2	103.6
August	1912-1967	56	189.8	188.5	78.1
	1968-2006	39	264.8	233.6	129.6

The August rainfall shows a much clearer increasing trend compared to the July rainfall. The statistics also support the July and August precipitation results before and after the change points (Table 2). In comparison with July rainfall, August rainfall during latter period has a larger mean and standard deviation than during the first period. Consequently, after late 1960s, August rainfall undergoes increases with large deviations.

4. The impacts of SST and changes in circulations

In this section, we try to investigate the SST and circulation changes in the July/August rainfall anomalies. First, to see the circulation change associated with the climate change in August rainfall, we have performed composite analysis for both the strong and weak August precipitation years (Fig. 2). The criterion for extreme August rainfall is the same as those shown in Fig. 1a. The ten strong August rainfall years (1969, 1972, 1980, 1985, 1987, 1993, 1998, 1999, 2000, and 2002) are roughly shown in recent years, in comparison with the eight weak August rainfall years (1950, 1953, 1960, 1964, 1973, 1975, 1977, and 1988). In the strong August years, the 500hPa geopotential height and 850hpa wind during August show that the southerly wind from the western Pacific was expanded westward into the Korean Peninsula with expansion of the WNP high. Due to this westward expansion of the WNP high, low level winds are squeezed and the water vapor may transport into the Korean Peninsula (Zhou and Yu, 2005[15]). The westward extension of the high that is probably responsible for the August rainfall. It is known in the recent climate as the "Bonin high" in some studies (e.g., Enomoto *et al.*, 2003[3], and Ha and Lee, 2007[5]). The climate change in August rainfall is sensitive to the behavior of the Bonin high. Another possible factor is the weakening of tropical easterly winds. The weakened easterly winds in the central/eastern Pacific imply the El Niño effect on August rainfall during boreal summertime. It will be shown to be more evident in the regression of SST anomalies against the August rainfall in the Korean Peninsula (Fig. 3).

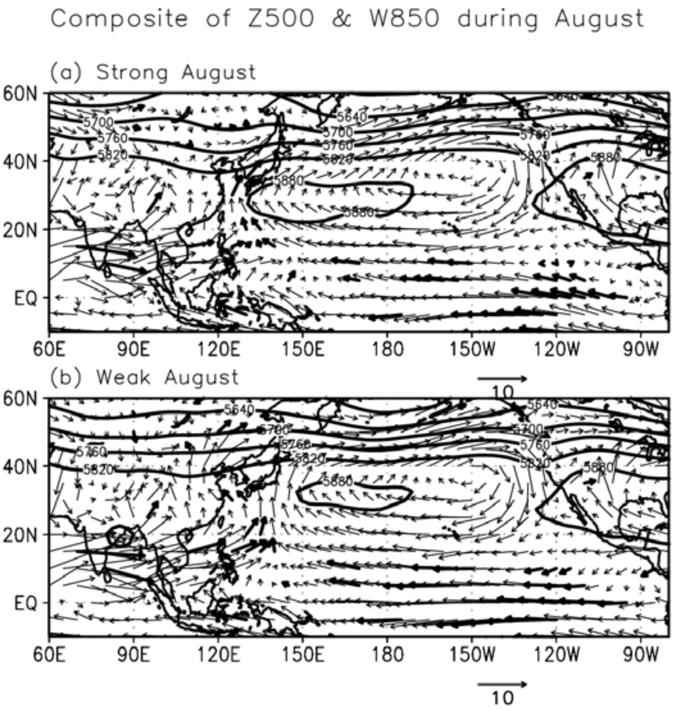
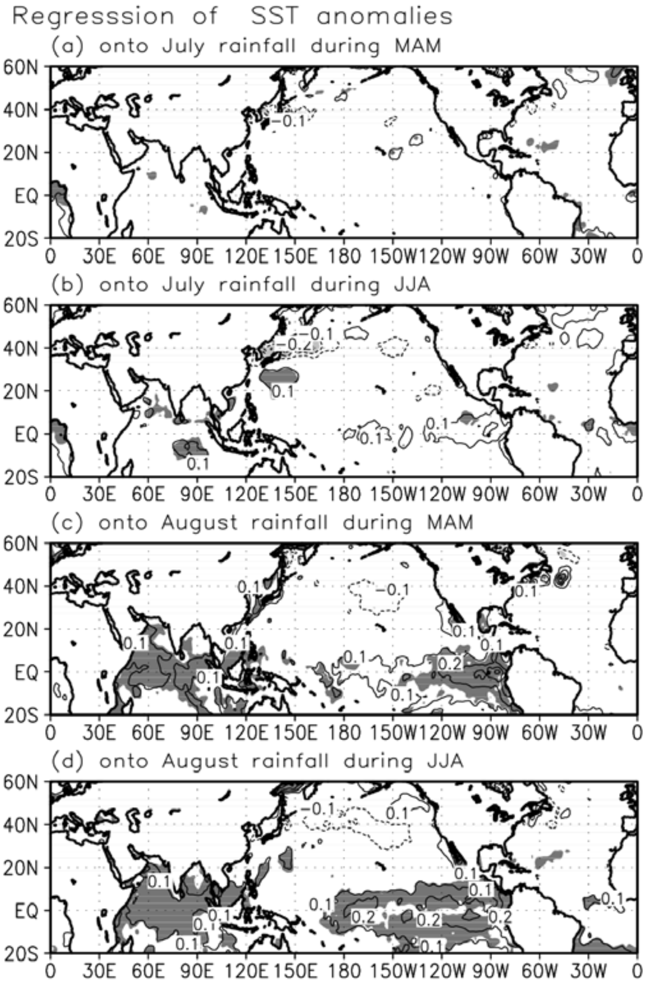


Figure 2. Composite field of 500hPa geopotential height (thick solid line) and 850hPa wind (arrow) during August for (a) strong and (b) weak August rainfall years. The thick wind vector indicates the value significant at a 90% confidence level.

The regression analysis of the SST anomaly against the July and August rainfall is performed from MAM to JJA. In the regressed SST field in lead times and concurrent time, the July rainfall exhibits the impacts of regional ocean variability (Fig. 3a and 3b). For example, during the summertime, warm anomalies in the WNP and cold anomalies over Korea and Japan appear. These may be associated with the East Asian summer monsoon rainfall front activity. The remote ocean (i.e., Indian Ocean and eastern Pacific) SST shows slightly weak warm anomalies. However, the August rainfall has impacts of remote ocean variability on intensity (Fig. 3c and 3d). A recent examination on global land monsoon rainfall variability showed similar SST anomaly structure and the result supports the remote Ocean impact on the August rainfall (Zhou *et al.*, 2008[16]).



Regresssion of SST anomalies

(a) onto July rainfall during MAM

(b) onto July rainfall during JJA

(c) onto August rainfall during MAM

(d) onto August rainfall during JJA

Figure 3. Regression of the SST anomaly during (a) MAM and (b) JJA against the July rainfall anomalies and during (c) MAM and (d) JJA against the August rainfall anomalies. The shading indicates the values significant at a 95% confidence level.

In particular, the Indian Ocean warming has a persistent impact on the August rainfall. Considering the increasing trend in Indian Ocean (Alory *et al.*, 2007[1]), the warm anomalies in the long-term trend may play a vital role in modulating the circulation change associated with the August rainfall.

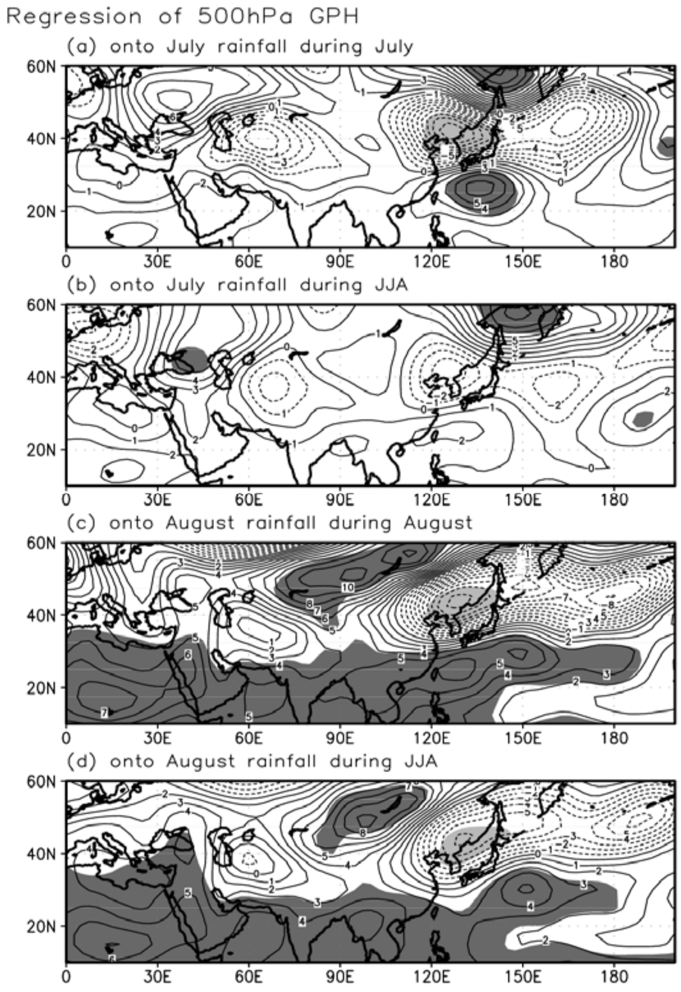


Figure 4. Regression of the 500hPa geopotential height during (a) July and (b) JJA against the July rainfall anomalies and during (c) August and (d) JJA against the August rainfall anomalies. The shading indicates the values significant at a 95% confidence level.

The WNP high with westward extension plays an important role in determining the intensity of the August rainfall. To look at the characteristics in large-scale circulation in detail, we have performed the regression analysis of the 500hPa geopotential height anomalies against July and August rainfall anomalies (Fig. 4). To observe the persistence on the rainfall anomalies, the regression of the summertime (i.e., June-July-August) height anomalies is carried out in Figs. 4b and 4d.

The July rainfall exhibits meridional wave structure, which is associated with the Pacific-Japan pattern (Nitta, 1983[11]). On the other hand, the August rainfall shows zonal wave-like pattern along the Eurasian continent. The structure also appears in the regressed 200hPa geopotential height anomalies (not shown). This structure represents an equivalent barotropic structure with large amplitude. The equivalent barotropic pattern is modulated by the enhancement of Asian jet stream via stationary Rossby wave. This suggests that the interannual variability of August rainfall is related to the stationary Rossby wave along the Asian jet stream. During the summertime, the regressed field against the August rainfall also exhibits a similar wave-like pattern, while the one regressed onto July rainfall does not show any meaningful structure. This indicates that the August rainfall has a steady atmosphere response compared with the July rainfall.

5. Summary and Conclusion

The August rainfall has increased with time, while the July rainfall did not show any significant rising trend. On the recent strengthening of August rainfall over the Korean Peninsula, the impacts of local and remote SST variability, and circulation were investigated in terms of the interdecadal variability of the July and August rainfall. The August rainfall is strongly related to the westward expansion of the subtropical WNP high and the presence of the Bonin high, which has an equivalent brotropic structure. In the regressed SST and circulation features, the July rainfall has impacts of regional ocean variability, and the August rainfall has impacts of remote ocean variability (i.e., eastern Pacific and Indian Ocean warming) on intensity. The August rainfall appears to have a more persistent wave-like structure for the regressed large-scale circulation than the July rainfall. This implies that the August rainfall has a more organized teleconnection than the July rainfall. The August rainfall also exhibits the extratropical Eurasian wave structure. The July rainfall is closely related to the PJ pattern, which is associated with the East Asian summer monsoon front movement. Consequently, the August rainfall appears in a different mechanism from the July rainfall. The August rainfall is more sensitive to the remote Ocean and large-scale circulation compared with the July rainfall. These results support that August rainfall is more useful for better seasonal predictions than July rainfall. These findings may contribute to the improvement in summer rainfall prediction.

Acknowledgments

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