ON INTERANNUAL CHARACTERISTICS OF CLIMATE PREDICTION CENTER MERGED ANALYSIS PRECIPITATION OVER THE KOREAN PENINSULA DURING THE SUMMER MONSOON SEASON

KYUNG-JA HA,* SUNG-KYU PARK and KI-YOUNG KIM
Department of Atmospheric Sciences, Pusan National University, Busan 609-735, South Korea

Received 12 September 2003
Revised 16 August 2004
Accepted 16 August 2004

ABSTRACT

To improve understanding of the characteristics of large-scale environments associated with summer monsoon precipitation in Korea, we have constructed an index to measure the Changma using area-averaged and period-averaged Climate Prediction Center merged analysis precipitation over Korea during the years 1979–2001. Strong and weak Changma years are defined as years in which the precipitation anomaly is over ±0.5σ. The domain and period for this analysis are selected over the Korean peninsula (31.25–41.25°N, 123.75–131.25°E) from late June to late July. In strong Changma years, strong upper level divergence occurs near the Korean peninsula, located at the entrance of the mid-latitude jet core, leading to low pressure in the lower layer. Between strong and weak Changma years, 850 hPa southwesterly flows are significant throughout the East China Sea and southern Japan.

Clear differences exist between strong and weak Changma years. Weak Changma is well correlated with a weak Pacific high, as seen in the changes in sea-level pressure and 500 hPa geopotential height, and wind speed in the lower level jet. Strong Changma is well correlated with strong migratory highs in northern parts of the Korean peninsula. It is shown that the long-term changes in summer monsoon rainfall, such as those between the two climate regimes of 1979–92 and 1993–2001, are characterized by a shift of maximum rainfall periods from late July to mid August. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Changma rainfall index; dynamical monsoon index; interannual characteristics; long-term changes

1. INTRODUCTION

Summer monsoon rainfall prediction is of great importance in the Far East Asian monsoon region. Monsoon rainfall, defined as the seasonal mean or intraseasonal mean rainfall, plays an important role in affecting water resources and agricultural affairs. Since ancient times, summer monsoon rainfall has been variously referred to as ‘Baiu’ (Japanese), ‘Meiyu’ (Chinese), and ‘Changma’ (Korean), all of which possess characteristics of an annual march and synoptic activities. They are characterized by frontal rain systems between the two major anticyclonic circulations over the subtropics and the polar regions. Many articles exist on the association between local summer monsoon rainfall and the Asian monsoon. The climatological intraseasonal oscillation (CISO) of the Asian summer monsoon has large regional differences. The dominant periodicities of CISO are about 30–40 days over both the Indian Ocean and the western Pacific (Lau and Chan, 1986; Wang and Xu, 1997) and about 60 days over the extratropics in East Asia and northern India (Wang and Xu, 1997). On the other hand, Kang et al. (1999) investigated the principal mode of Changma from the perspective of climatological variation of the Asian summer monsoon.

* Correspondence to: Kyung-Ja Ha, Department of Atmospheric Sciences, Pusan National University, Busan 609-735, South Korea; e-mail: kjha@pusan.ac.kr

Copyright © 2005 Royal Meteorological Society
Previous studies on the interannual variability of the East Asian summer monsoon have emphasized the thermal effect of the Tibetan Plateau (Nitta, 1983; Luo and Yanai, 1984). The thermal state and convective activities over the western Pacific warm pool are also considered to play an important role in the interannual variability of the East Asian summer monsoon (Nitta, 1987). Also, the pronounced year-to-year variability is partially explained by El Niño and the southern oscillation (ENSO; Zhang et al., 1996). However, the linkage between the Far East Asian monsoon rainfall and ENSO still remains unclear.

Numerous studies also exist on the decadal variability of the East Asian summer monsoon, and many of these studies have investigated the summer rainfall over central China and southern Japan (Yatagai and Yasunari, 1994; Nitta and Hu, 1996). Ho et al. (2003) have examined long-term climate change in Korea. Apparently, the cooling trend of the surface temperature in Mongolia due to deforestation and expansion of the arid area (Wang and Li, 1990; Xue, 1996) might be associated with the climate change (Ho et al., 2003).

It is well known that Changma in Korea is accompanied by the northward penetration of the subtropical Pacific high to the south of the Korean peninsula (Lim, 1997). Oh et al. (2000) found that, at the onset and retreat times of Changma, the geopotential height increases rapidly over the Korean peninsula and southern Japan, and that the increase in geopotential height in the mid–high latitudes persists for several days prior to the Changma onset. Lu et al. (2001) have also emphasized that Changma retreats are associated with planetary-scale teleconnection patterns of circulation in the mid–high latitudes.

Because of the importance of predictability of summer monsoon rainfall, our attention should revert back to the understanding of year-to-year variability. Many studies (Webster and Yang, 1992; Goswami et al., 1999; Lau et al., 2000) about the variability of the Asian summer monsoon have mostly targeted South Asia, East–Southeast Asia, and the Indo-Pacific region. Changma in Korea has been poorly understood on an interannual time scale. The purpose of the present study is to provide a more comprehensive understanding of the interannual variability of summer monsoon rainfall over Korea and the causes of this in the large-scale circulations. To accomplish our objective, we will define the interannual characteristics of mean rainfall during Changma with the use of climatic analysis data. In particular, we have recently experienced record-breaking torrential rainfall during the Changma season or before/after Changma. However, it is still uncertain whether these extreme events are episodic or a part of long-term variation in the climatic regime. We attempt to investigate the characteristics of the long-term changes, such as decadal variations in circulation states associated with precipitation.

2. METHOD

2.1. Data

In this study, summer monsoon rainfall is measured by the 5 day (pentad) mean of the Climate Prediction Center merged analysis of precipitation (CMAP) data, for the years 1979–2001. CMAP is known as a representative data set that combines ground-based rain gauges and satellite-based observations (Xie and Arkin, 1997). Even though the gridded pentad rainfall has been examined as being useful for diagnostics (Xie et al. 2003), we used the CMAP 10 day mean rainfall data to obtain the interannual variability, avoiding the optional selection of ground station data. The data used for the large-scale characteristics also include the sea-level pressure (SLP), geopotential height at 700, 500 and 200 hPa, wind at 850 and 200 hPa, and specific humidity at 850 hPa from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. These NCEP–NCAR reanalysis data and CMAP data have the same horizontal resolution of 2.5° × 2.5° longitude–latitude.

To examine the characteristics of the interannual variability and long-term variability of the summer monsoon rainfall over the Korean peninsula, we performed composite analyses for strong versus weak Changma years, later versus earlier regime, and long-lasting versus short-lasting Changma years. We also performed a Student’s t-test to obtain the significance for composite differences. To show the decadal variation, we only analysed rain-gauge information from ground-based stations.
2.2. Changma rainfall index

The development of the monsoon rainband associated with Meiyu in China and Baiu in Japan usually occurs around mid June, whereas Changma in Korea starts in late June (Ho and Kang, 1988). The transient evolution of the monsoon rainband in northeast Asia is presented by a maximum rain axis over 8 mm/day, as shown in Figure 1. In relation to the climatological mean of 1979–2001, the northward progress of a 10 day maximum rain is obviously seen from early June to late July from the south of Japan to northern Korea. This northward progress is well matched to the progress or intensity of the North Pacific high (NPH) and the Okhotsk high. In mean SLP fields during mid July, the maximum rain axis occurs in the trough between the NPH and the Okhotsk high. In mean SLP fields during mid July, the maximum rain axis occurs in the trough between the NPH and the Okhotsk high (refer to the thin line in Figure 1).

In late June, when the maximum rain axis lies in Kyushu in Japan, Jeju island, and the East China Sea, the rainfall in southern Korea increases. Migrating highs from the interior of China might also be correlated with the progress of the maximum rain axis after mid July. During the transition from early July to mid July, there is a distinct phase change when maximum rain axes migrate to the north. Although interannual anomalies are often highly episodic in time and in space, it is obvious that monsoon flows and Baiu fronts influence the initiation and characteristics of the Korean Changma rainfall. During early July, the maximum rain axis is separated into two lines. A broken maximum rain axis during early July may imply a complex association to either Meiyu or Baiu. After late July, the maximum rain axis of $R > 8$ mm/day is weakened and disappears. It is apparent that the onset and retreat of maximum rain axes for CMAP are beneficial to define the Changma frontal rain index.

From late June to late July, the influence of maximum rain axes appears around Korea. We define this period as the Changma season and the area influenced as the Changma area (rectangular box in Figure 1), and then define the Changma rainfall index (CRI) as follows:

$$CRI = \text{area average of (late June–late July 10 day precipitation rate, over lon}}$$

$$= 123.75–131.25^\circ \text{E, lat} = 31.25–41.25^\circ \text{N)}$$

Figure 1. Schematic diagram showing the maximum rain axes in rainbands shown by CMAP data around the Korean peninsula from early June to late July. The solid lines represent the axes of the maximum rainbands, $R > 8$ mm/day for 10 day mean precipitation. Mean SLP during mid July is shown in the background contours. The rectangular box over the Korean peninsula indicates the area influenced by the maximum rain axes from late June to late July (E: early; M: middle; L: late)

Copyright © 2005 Royal Meteorological Society

Close scrutiny of the intraseasonal variation of the maximum rain axis and the maximum axis (over 6 m/s) of wind speed at 850 hPa (solid line in Figure 2) shows that the variations of rain axes in the monsoon season closely resemble those of low-level winds, indicating moisture transport from a warm temperature pool. The 850 hPa wind maximum axis is observed at the trough axis between the warm NPH and the cold Okhotsk high. As expected, from the 500 hPa geopotential height, the spatial pattern of 10 day 5850 gpm for the NPH (shown as a dashed line in Figure 2) is also very similar to that of the intraseasonal variation of the maximum rain axis. Thus, the characteristic variation of the maximum rain axis for the 10 day mean is well correlated to the Asian monsoon flow from the climatological point of view.

2.3. Interannual variability

We now investigate the interannual variations of Changma rain. A CRI count for Changma rainfall is shown in Figure 3. The mean CRI = 7.1 mm/day, and the strong and the weak Changma years are defined as years
in which the precipitation anomaly is more than ±0.5σ. There are 6 years and 7 years respectively in the categories of weak and strong years. The CRI shows that weak years are mostly seen in the early period, and strong years in the late period.

2.4. Empirical orthogonal function analysis of the summer monsoon rainfall

The monsoon variations are characterized by several major time scales associated with seasonal marches and intraseasonal oscillations (Wang and Xu, 1997). To describe the climatological variations, empirical orthogonal function (EOF) analysis is applied to the climatological pentad CMAP data for summertime (Figure 4). The results of the EOF analyses are similar to those applied to pentad high cloud fractions obtained by Kang et al. (1999), except for a more southward shift of the spatial pattern in the eigenvector. The first mode shows an annual mode. In the second eigenvector (Figure 4(c)), the zonally elongated pattern of positive values from central China to the North Pacific is very similar to the East Asian rainband associated with Meiyu and Baiu. The time series in Figure 4(d) shows that the second mode develops during early summer. The second mode is assumed to be a monsoon mode. The third eigenvector, shown in Figure 4(e), is characterized by positive

Figure 4. First three leading eigenvectors and associated time series obtained from the EOF analysis of the 5 day mean climatological variation of CMAP from May to August during 1979–2001. Shaded area represents positive region.
values over a zonal band crossing the Korean peninsula, and the associated time series (Figure 4(f)) has positive values from mid June to mid July. Both the spatial pattern and associated time series indicate that the third eigenmode appears to be related to the Changma in Korea. Therefore, Changma can be represented by the third mode in this study.

Results of EOF analyses in strong and weak Changma years are shown in Figure 5. In strong years, there are larger positive values from east China to Japan in the third eigenvector, compared with those in weak years. From the associated time series of the third eigenvector, the retreat of Changma is late in strong years compared with weak years. Similar results are shown in the time series for the second eigenvector. The third mode in weak years explains a greater fraction of the total variance than that in strong years. On the other hand, Changma rainfall is positively correlated with the rainfall in the Indian monsoon region, especially in the northern part of the Indian continent, and negatively correlated with the rainfall near the South China Sea (SCS; 10°N, 120°E). Compared with the third eigenvector in all years (Figure 4(e)), it is found that there is a marked contrast in the axis of strong positive values of the third eigenvector over the East China Sea for the strong and weak Changma years.

3. COMPOSITE DIFFERENCES

To examine the characteristics of synoptic fields associated with interannual variability of the monsoon rainfall over the Korean peninsula, we performed composite analyses for strong versus weak Changma years and composite differences with various variables. As a result, the CRI difference is characterized by the SLP, 500 hPa geopotential height, and winds at 200 and 850 hPa.

3.1. SLP and upper level geopotential height

Figure 6(a) and (b) shows the SLP composites for the strong Changma years and the strong minus weak Changma years. The shaded areas show the regions significant at the 95% confidence level. We used the Student t-test to assess the significance of the composite difference of mean strong and weak Changma years. This test has assumptions about the independence and randomness of the data, and good validation is required when there are fewer than 30 observations.

For the difference in SLP between the strong and weak years, significant positive differences are seen in eastern Mongolia. A trough is located between these two positive SLP centres due to the NPH and the migrating high over northeastern China. Rectangular squares in these two higher SLPs are considered for the Changma index in Section 4 and Table I.

Figure 6(c) and (d) is the same as Figure 6(a) and (b) but shows the 500 hPa geopotential height. There is a strong and deep trough axis over the Bering Sea and the Sea of Okhotsk, and a trough over the west of Korea in strong years. From the difference field (Figure 6(d)), the most important thing is the higher NPH in the northwest Pacific. Compared with the SLP pattern of Figure 6(b), the 500 hPa geopotential height is dominant over the NPH and that over the north of Korea is shallow.

3.2. Winds

We show the 200 hPa wind (Figure 7) with u and v components in strong Changma years and the composite differences in u-component wind and v-component wind between strong and weak Changma years. From Figure 7(a), the u-component wind (shading) and the v-component wind (contour) show that the cyclonic circulation in the region west of Korea is enhanced by the increasing meandering jet.

It is found that the significant circulation is cyclonic in the region through the west and east of Korea. This cyclonic circulation is associated with the jet core developing close to the east of Korea. The jet streak in the downstream region over the east of Korea may induce strong divergence in the elevated layer over the surface trough. We have chosen this downstream jet as one of the Changma indices. Figure 8 shows the 850 hPa wind field indicating low-level transport for moisture. Advection of moist and warm air by the low-level winds is essential for generating convective instability and sustaining the convective activity (Ninomiya, 1980).
Figure 5. As Figure 4, except for strong and weak Changma years
Figure 6. (a) Composite field for SLP of strong Changma years. (b) The difference in SLP between weak and strong Changma years. (c) As (a), except for 500 hPa geopotential height. (d) As (b) except for 500 hPa geopotential height. Shaded areas represent significant areas (95% confidence level). The two rectangular boxes in the significant area are used to construct an index.

significant area is for the magnitude of the wind vector in the difference field (Figure 8(b)). Figure 8(b) shows a north–south pattern consisting of an anomalous anticyclone over the northwestern Pacific and a cyclonic anomaly around Korea. This meridionally oriented sequence of an alternation of low and high is similar to the Pacific–Japan pattern shown by Nitta (1986, 1987). In this context, it has been known that above (below)-normal pressures and suppressed (enhanced) convection near the Philippine islands and the subtropical western Pacific Ocean are favourable for enhanced (subdued) rainfall over Japan (Nitta, 1987). In Figure 8(b), the low-level jet is associated with the merging of the southwest flow and the southeast flow from lower latitudes. However, the southwest flow is greater than that of the southeast flow. It is obvious to note that the low-level jet from the southwest flow over the Asian summer monsoon has been associated with a strong Changma.

4. EVALUATION OF SUMMER MONSOON INDICES

Many studies (Webster and Yang, 1992; Goswami et al., 1999; Lau et al., 2000) have derived indices for measuring the Asian monsoon. In this study, to investigate the Changma index for the interannual variability of the rainfall characteristics over Korea, the significant difference values in the previous figures (rectangular squares in Figures 6 and 8) are considered. The Changma indices described in this study are associated with the interannual variability of the area–period-averaged rainfall. Firstly, we try to compare the Changma indices of this study and the indices used in the previous studies mentioned above. Table 1 shows the different correlation coefficients (CCs) for CRI and other indices. Here, CCs are calculated using the complete 1979–2001 record length, the years selected as the strong and the weak years, the years except for strong Changma years, and the years except for weak Changma years. These CCs will reveal the causes of strong and weak Changma. A 95% confidence level was used.
The previous indices, such as RM2 for the regional monsoon in East Asia (Lau et al., 2000) and MHI (monsoon Hadley index) (Goswami et al., 1999) as well as the NINO3 sea-surface temperature (SST) index are used to calculate the CC for the CRI. The MHI is a measure of baroclinic instability, which is obtained from the difference of \( v \)-component winds between the upper and lower levels over 10–30°N, 70–110°E; and the RM2 is for the 200 hPa \( u \)-component wind difference between the mean over 25–35°N, 110–150°E and the mean over 40–50°N, 110–150°E.

In this study, the SLP index is in three parts: the south index for the area over 20–35°N, 135–150°E; the north index for the area over 50–57.5°N, 115–127.5°E; and the total of the south plus the north. The 500 hPa geopotential height (25–35°N, 135–152.5°E), 200 hPa wind (40–45°N, 137.5–155°E), and 850 hPa wind (32.5–37.5°N, 127.5–147.5°E) are used to measure the interannual variability of Changma from the significant values mentioned in Section 3.
Figure 8. Composite fields for (a) the 850 hPa wind of strong Changma years and (b) the difference in the 850 hPa wind between weak and strong Changma years. The shaded areas represent significant areas (95% confidence level) and are for wind speed.

In relation to the previous indices, we have shown that the CCs are not significant. Therefore, it is unsuitable to explain the strong and the weak rainfall characteristics over Korea using RM2, MHI, or NINO3 SST.

Among the indices from this study, the SLP area index has the highest CC for all years (1979–2001) and for the strong and weak Changma years. From the CC for the years except for the strong Changma years and vice-versa the north and south SLP area indexes are important for explaining rainfall characteristics in strong and weak years, respectively. It is interesting to note that the migrating high over the north of Korea may play a significant role in reinforcing the strong Changma over Korea, compared with the NPH over the south of Korea. The 500 hPa area index is well correlated to the weak Changma over the south of Korea and the 850 hPa wind area index is also correlated to the weak Changma. On the other hand, the 200 hPa wind area index does not represent well the strong and the weak Changma years separately.

As a result, there are distinct characteristics for the strong and the weak Changma years in terms of the SLP area index. The north area index of the SLP area index might be associated with frequent occurrences of the migrating highs over northeastern China. However, the south area index of the SLP area index and the 500 hPa geopotential height area index associated with the strength of the Pacific high over the south of Japan might be correlated to the weak Changma.
Table I. Correlation coefficients between precipitation variability and variables (indices). The four precipitation time series are used, which are for all years from 1979 to 2001, strong and weak Changma years, years except for strong Changma, and years except for weak Changma. The variable indices include ENSO SST index, MHI, RM 2, area-averaged SLP index, area-averaged 500 hPa geopotential height index, and area-averaged wind index. Areas used in averaging are different from each variable, such as Figure 6 (SLP, H500), Figure 7 (UV200) and Figure 8 (UV850).

<table>
<thead>
<tr>
<th>Index</th>
<th>1979–2001</th>
<th>Strong and weak Changma years</th>
<th>Years except for strong Changma</th>
<th>Years except for weak Changma</th>
</tr>
</thead>
<tbody>
<tr>
<td>NINO3</td>
<td>0.24</td>
<td>0.26</td>
<td>0.26</td>
<td>0.02</td>
</tr>
<tr>
<td>MHI</td>
<td>−0.07</td>
<td>−0.16</td>
<td>0.02</td>
<td>−0.07</td>
</tr>
<tr>
<td>RM2</td>
<td>−0.28</td>
<td>−0.36</td>
<td>−0.17</td>
<td>−0.45</td>
</tr>
<tr>
<td>SLP area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South + north</td>
<td>0.64</td>
<td>0.70</td>
<td>0.60</td>
<td>0.37</td>
</tr>
<tr>
<td>South</td>
<td>0.57</td>
<td>0.62</td>
<td>0.62</td>
<td>−0.17</td>
</tr>
<tr>
<td>North</td>
<td>0.49</td>
<td>0.57</td>
<td>0.35</td>
<td>0.50</td>
</tr>
<tr>
<td>500 hPa HGT area</td>
<td>0.63</td>
<td>0.68</td>
<td>0.67</td>
<td>−0.04</td>
</tr>
<tr>
<td>200 hPa wind area</td>
<td>0.46</td>
<td>0.51</td>
<td>0.42</td>
<td>0.31</td>
</tr>
<tr>
<td>850 hPa wind area</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.24</td>
</tr>
</tbody>
</table>

5. LONG-TERM VARIATION

5.1. A trend

The recent characteristics of rainfall in Korea from the mid 1990s, especially for the summer, show a significant difference from the climatological features in earlier times. Record-breaking rainfall and flash floods have been experienced during the month of August since 1998 (Yun et al., 2001; Hwang and Park, 2000). However, it is still uncertain whether these extreme events are episodic or part of a long-term climate variation. In this section, we attempt to investigate the characteristics of long-term change, such as decadal variation, for two climate regimes of earlier and later years.

To examine the long-term variability of the summer monsoon rainfall, rainfall data for 13 representative stations (Table II) over Korea for the period of May–October of 1979–2001 are used. Two peaks of rainfall (Ib: 25 June–29 July; Ia: 14 August–12 September) are seen from the 23 year time series of pentad rainfall during 1979–2001 (not shown). More than half of the annual rainfall in Korea is concentrated in these two periods.

Table II. Location information for the surface weather stations used in the present study

<table>
<thead>
<tr>
<th>Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gangneung</td>
<td>37°45'</td>
<td>128°54'</td>
<td>26.0</td>
</tr>
<tr>
<td>Seoul</td>
<td>37°34'</td>
<td>126°58'</td>
<td>85.5</td>
</tr>
<tr>
<td>Incheon</td>
<td>37°29'</td>
<td>126°38'</td>
<td>68.9</td>
</tr>
<tr>
<td>Ulleung-do</td>
<td>37°29'</td>
<td>130°54'</td>
<td>221.1</td>
</tr>
<tr>
<td>Chupungnyeong</td>
<td>36°13'</td>
<td>128°00'</td>
<td>245.9</td>
</tr>
<tr>
<td>Pohang</td>
<td>36°02'</td>
<td>129°23'</td>
<td>5.6</td>
</tr>
<tr>
<td>Daegu</td>
<td>35°53'</td>
<td>128°37'</td>
<td>57.8</td>
</tr>
<tr>
<td>Jeonju</td>
<td>35°49'</td>
<td>127°09'</td>
<td>51.2</td>
</tr>
<tr>
<td>Ulsan</td>
<td>35°33'</td>
<td>129°19'</td>
<td>31.5</td>
</tr>
<tr>
<td>Gwangju</td>
<td>35°08'</td>
<td>126°55'</td>
<td>70.9</td>
</tr>
<tr>
<td>Busan</td>
<td>35°06'</td>
<td>129°02'</td>
<td>69.2</td>
</tr>
<tr>
<td>Yeosu</td>
<td>34°44'</td>
<td>127°44'</td>
<td>67.0</td>
</tr>
<tr>
<td>Jeju</td>
<td>33°31'</td>
<td>126°32'</td>
<td>22.0</td>
</tr>
</tbody>
</table>

summer rainy periods (Ho and Kang, 1988). The primary rainy period is termed Changma. As the monsoon trough moves further north to northeastern China, the primary rainy period ends. When the monsoon trough retreats southward of the Korean peninsula, the secondary rainy period, known as the Autumn Changma, which is called ‘Shurin’ in Japan (Matsumoto, 1992), starts. During the secondary rainy period, typhoons account for some of Korea’s precipitation.

Using mean rainfall for the two peaks \( I_a \) and \( I_b \) and the rainfall during the period between the two peaks, i.e. \( II \) (30 July–13 August), the turning point from the earlier regime to the later regime was investigated. The turning point for the year is computed as the following two-peak index:

\[
\text{Two-peak index} = \frac{I_a + I_b}{2} - II
\]

The time series of two-peak indices are shown in Figure 9(a). A negative value implies one-peak characteristics and a positive value represents two-peak characteristics. The two-peak index decreases abruptly in 1993 and since then negative values appear frequently. Therefore, 1993 is selected as the turning point. Years before and after the turning point are termed the earlier regime (PI, 1979–1992) and later (PII, 1993–2001) regime respectively.

Figure 9(b) shows the time series of regime-average pentad rainfall for both regimes (five-point moving average) of later and earlier regime. From late July to mid August the rainfall climate changes from light rainfall to heavy rain characteristics as the regime changes. This means that the withdrawal time for Changma has tended to be later in the recent decade, so the last decade has many more years of long Changma than the earlier decade. Lu et al. (2002) mentioned that the withdrawal of Changma is important for determining the

![Figure 9](image-url)

Figure 9. (a) Time series of two-peak index (solid line) and 5 year averaged two-peak index (dashed line). Years before and after the turning point are termed the earlier (PI) and later (PII) regimes respectively. (b) Time series of regime average pentad rainfall for both regimes (five-point moving average) of later (dashed line) and earlier (solid line) regimes.
rain amount for the summer monsoon season. On the other hand, rainfall decreases in the later regime during the secondary rainy period. In this study, however, we focus on the period from late July to mid August associated with Changma withdrawal.

Composite analyses are performed for two climate regimes during June–August. We depict differences of the mean CMAP between the earlier and later regimes. Figure 10(a) and (b) shows the CMAP (mm/day) in the later regime and the difference between the two regimes. The shaded areas show the significant regions at the 95% confidence level. There is significantly more rainfall along the edge of the continent, especially over the East China Sea, Kyushu and south China in the later regime.

Figure 10(c) and (d) is the same as Figure 10(a) and (b) but shows the 700 hPa geopotential height. Significant positive values are represented over northeast China and Mongolia in the composite difference (Figure 10(d)). Similar results appear at 500 hPa (not shown). Ho et al. (2003) examined the long-term changes in Korean precipitation between the earlier (1954–77) and later (1978–2001) regimes, showing that increased geopotential height over the Asian continent leads to a strengthening of the anticyclonic circulation anomaly in the later regime. Therefore, a northerly wind is enhanced in East Asia along the eastern boundary of the anticyclone, which transports relatively cool and dry air to East Asia. The northerly wind later interacts with the prevailing southerly wind that is warm and moist. Hence, moisture convergence and convective activity intensify, increasing the chance of heavy rainfall. In the composite difference for 850 hPa wind (not shown), an anticyclonic circulation anomaly associated with positive values in Figure 10(d) emerges over northeast China and Mongolia. As a result, a northerly wind anomaly appears in Korea, and, as mentioned above, convergence occurs between cold air associated with the anticyclonic circulation anomaly and warm air originating from the SCS to the south of the Korean peninsula. This may result in strong baroclinicity to the south of the Korean peninsula, which may contribute to more rainfall over that region in the later regime, as shown in Figure 10(b). On the other hand, the increased rainfall over south China in the later regime may be associated with the stronger southwesterly over the south of that region.

Figure 10. (a) Precipitation (mm/day) composite during June–August in the later regime. Contour interval is 2 mm/day. (b) Composite difference in precipitation between the later and earlier regimes. Contour interval is 0.5 mm/day, and zero line is not shown. (c) As (a), except for 700 hPa geopotential height. Contour interval is 20 m. (d) As (b), except for 700 hPa geopotential height. Contour interval is 3 m. Shaded areas represent significant areas with a 95% confidence level.
5.2. Long and short Changma

As mentioned in Section 5.1, the last decade has more years of long Changma than the early decade. Comparisons between the long and short Changma with rainfall amounts during late July to mid August (30 July–13 August) are important for examining the influence of the late withdrawals of Changma. This period is defined as a late peak period in this study. Figure 11(a) shows the time series of mean precipitation anomalies over Korea during the late peak period. Long and short Changma years are defined as years in which precipitation anomalies are more than $\pm 1\sigma$ in the later and earlier regimes respectively. Long Changma years are selected as 1993, 1997, 1998, and 1999 in the later regime, and short years as 1984, 1988, and 1990 in the earlier regime.

![Figure 11](image-url)

Figure 11. (a) Time series of mean precipitation anomaly over Korea during the late peak period (30 July–13 August). The data used are 5 day averaged (pentad) precipitation data of 13 weather stations in the Korean peninsula. The years when rainfall is less than $-\sigma$ in the earlier regime and more than $\sigma$ in the later regime are denoted by diamonds (short Changma) and circles (long Changma) respectively. SLP composites during the late peak period (b) in the long Changma years and (c) in short Changma years. The climatology of SLP in (d) July and (e) August from 1979 to 2001.
Composite analyses for long and short Changma years are performed. Figure 11(b) and (c) shows SLP composites in long Changma years and in short Changma years. In the long Changma years (Figure 11(b)), ridges associated with the NPH extend toward the Sea of Okhotsk and south of Japan and a trough develops between these ridges, with an inclined NPH northeastward from the SCS. The direction of the NPH boundary might be associated with a continuous moisture supply from the warm pool area. On the other hand, the ridge extends toward Korea and the Aleutian low develops in short Changma years (Figure 11(c)). From these results, positive values in composite difference appear over the northwest Pacific, north of the Okhotsk Sea and the Bering Sea, and negative values around Korea. Similar features are evident in the 700 hPa geopotential height composite difference (not shown).

Figure 11(d) and (e) indicates the climatology of the SLP in July and August respectively. In July, the NPH extends toward the south of Japan and the Sea of Okhotsk. In August, on the other hand, the NPH extends toward Korea and Japan. When compared in Figure 11(b) and (c), the climatology of the SLP in July and August is similar to the composites for long and short Changma years respectively. As shown in the 200 hPa geopotential height, the Tibetan High extends more to the northeast in the short Changma years compared with the long Changma years, which is similar to the climatology of the 200 hPa geopotential height in August. In addition, the 200 hPa geopotential height field in the long Changma years resembles the climatology of July. These results mean that, in the long Changma years, the pressure patterns in July are maintained longer at both the surface and upper level synoptic fields during the late peak period.

In the 850 hPa wind composites (Figure 12(a) and (b)), a southwesterly is extended from the SCS toward the Korean peninsula in the long Changma years. This southwesterly provides moisture to the Korean peninsula and causes heavy rain. In the short Changma years, however, the Korean peninsula is not on the path of the southwesterly because of the circulation associated with the expansion of the NPH toward the Korean peninsula. In the 200 hPa wind composites (Figure 12(c) and (d)), the westerly jet stream moves northward so that it is weakened around the Korean peninsula in the short Changma years. Lu (2002) also found that, around Korea, the upper level jet is weakened and moves poleward for early withdrawals.

Figure 12. The 850 hPa wind composites in (a) the long Changma years and (b) the short Changma years. 200 hPa wind composites in (c) the long Changma years and (d) the short Changma years. Contour (interval 5 m/s) of right panel represents wind speed
Figure 13 shows the 850 hPa water vapour flux divergence composites. In the composite difference (not shown), significant negative values are found to the east (the East Sea of Korea and Japan) and southwest (eastern south China) of Korea, so the flux convergence of water vapour over these regions is stronger in long Changma years. On the other hand, water vapour flux convergence is seen from the southwest to northeast around Korea in the long Changma years. Therefore, the supply of moisture to the Korean peninsula due to the southwesterly and water vapour flux convergence in the lower troposphere leads to increased rainfall over Korea during the late peak period.

6. SUMMARY AND CONCLUSIONS

We have used the CMAP 10 day mean field to depict the intraseasonal variability of the summer monsoon rainband in the western Pacific. Maximum rain axes over 8 mm/day are used to investigate the northward evolution of the summer frontal rain characteristics. The local CRI over Korea is defined as an area-mean CMAP during the Changma period from late June to late July from the time variation of the maximum rain axis. From the results of the EOF analyses applied to the CMAP data, the second mode depicts the East Asian rainband, referred to as Meiyu and Baiu, and the third mode appears to be related to the Changma in
Korea. Also, the retreat of the Changma is late in strong Changma years, and Changma rainfall is positively correlated with the rainfall in the Indian monsoon region, especially that in the northern part of the Indian continent, and negatively correlated with the rainfall near the SCS (10°N, 120°E). In order to construct an index associated with the interannual variability of CRI, composite fields for SLP, 500 hPa geopotential height, 200 and 850 hPa winds are investigated.

From the composite analyses, a strong Changma is characterized by the strengthening of the NPH (in SLP and 500 hPa geopotential height) over the northwest Pacific and by the frequent occurrence of the migrating high (in SLP) over northeastern China. These are well represented in the Changma indices. For the 200 hPa wind, cyclonic circulation over northwestern Korea is seen in strong Changma years. This cyclonic circulation is associated with the jet core developing to the east of Korea. This jet streak in the downstream region may induce strong divergence over the surface trough. At 850 hPa, the southwesterly is strongly extended from the Bay of Bengal through the East China Sea to Japan in the strong Changma years. The downstream jet over the east of Korea and the southwesterly around southern Japan are also represented in the Changma indices.

The CRI is more significantly correlated to the indices in SLP, 500 hPa geopotential height, 200 hPa wind and 850 hPa wind than the previously defined indices of MHI, RM2 and NINO3. An important approach in this study is to separate the indices in terms of the strong and the weak Changma years. The migrating high in northeastern China is associated with the Changma, which is well represented in the SLP field. On the other hand, both the NPH over the northwest Pacific and the 850 hPa wind index are associated with the weak Changma.

To examine the long-term variability of the summer monsoon rainfall, we have analysed the rainfall data for 13 representative stations over Korea for the period of May–October of 1979–2001. Pentad rainfall shows two peaks in the earlier regime (1979–92), but only one peak in the later regime (1993–2001). From late July to mid August, the rainfall climate changes abruptly from a dry and light rainfall to heavy rain characteristics. This means that the withdrawal time for Changma has tended to be late in the recent decade.

In the composite analyses for CMAP in the earlier and later regime during June–August, there is significantly more rainfall along the edge of the continent, especially over the East China Sea, Kyushu and south China in the later regime. On the other hand, there is little difference in rainfall between the earlier and later regimes over the Korean peninsula.

The later decade has many more years of long Changma than the early decade. By using the time series of mean precipitation anomalies over 13 Korean stations during the late peak period (from late July to mid August), long and short Changma years are selected for the later and earlier regimes respectively. In the long Changma years, SLP ridges associated with the NPH extend toward the Sea of Okhotsk and south of Japan, and a trough develops between these ridges. In the short Changma years, however, the ridge extends toward Korea. The climatology of SLP in July is similar to the composite for long Changma years, and that in August is similar to the composite for short Changma years. A similar feature is also found in the 200 hPa geopotential height climatology; the same result is seen (not shown). These results mean that, in the long Changma years, pressure patterns in July are maintained longer on both the surface and upper level synoptic fields during the late peak period.

At 850 hPa, the southwesterly is extended from the SCS toward the Korean peninsula in the long Changma years. In the short Changma years, however, the Korean peninsula is not on the path of the southwesterly because of the circulation associated with the expansion of the NPH toward the Korean peninsula. In the short Changma years, the upper level jet moves northward and is weakened around the Korean peninsula.

As a result, there is little change of total rainfall during summer (June–August) over Korea. However, from late July to mid August there is more rainfall in the later regime because the July pattern is maintained longer on both the surface and upper level synoptic fields in that regime. On the other hand, there is no significant difference in SST between the earlier and later regimes (not shown). It is not clear whether the variation of Korea rainfall during the late peak period is a climatological variation. It is important to understand better the causes of change in summertime precipitation patterns and their predictability, and further investigations of these phenomena should be undertaken.
We gratefully acknowledge Song Yang for helpful discussions on an earlier version of this paper. This material is based upon work on ‘Monsoon and Changma’ supported by a Meteorological & Earthquake R&D Grant from the Korean Meteorological Administration. We would like to acknowledge the support from the KISTI (Korea Institute of Science and Technology Information) under ‘The Fifth Strategic Supercomputing Support Program’ with Dr Min-Su Joh as the technical supporter. The use of the computing system of the Supercomputing Center is also greatly appreciated.

REFERENCES