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Climatological characteristics and long-term variation of rainy season and torrential rain over DPR Korea

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ABSTRACT

Understanding extreme precipitation variability in Democratic People's Republic of Korea (DPRK) is important for monitoring and predicting droughts and floods, which is crucial for agricultural activities and water resources management in the country. Observed daily (hourly) precipitation data from 181 stations in DPR Korea during 1960–2007 (1969–2007) was used to analyze the onset, retreat and length of the rainy season (called Jangma in DPRK, Changma in South Korea, and Meiyu in the Yangtze basin of China), and to examine the climatological features and long-term change of torrential rains. The results showed: (1) The Onset, Retreat and Length of Rainy Season (O-RS, R-RS and L-RS) experienced an obvious inter annual and decadal variability, and they also had a good correlation with El Niño (La Niña), with some differences from those found in South Korea; (2) The linear trend of O-RS was 1.9day/decade during 1960–2007, indicating a gradually delayed O-RS, and the R-RS were getting earlier with a rate of −2.7day/decade, leading to a shortening L-RS at a rate of −4.7day/decade; (3) Regional differences of the numbers of Torrential Rain (TR) were obvious, which was related to the orographic effect, with the south and northwest of the study area registering the most frequent TR events; We also found that the frequency, intensity and amount of annual TR events generally increased during the last 4 decades; (4) The annual number of TR events with amount of precipitation more than 100 mm/6 h increased from 4.2 times (1974–1983) to 7.4 times (2003–2012), and the annual number of extremely intense TR more than 200mm/12 h also increased from 0.6 times to 1.2 times over the same two time periods.

1. Introduction

The Democratic People's Republic of Korea (DPRK) is located in Northeast Asia. It is affected largely by the East Asian monsoon in summer and Torrential Rain (TR) events are highly concentrated in the Rainy Season (RS). Because of the significant inter annual variability of the East Asian monsoon and the relationship between the intensity of summer monsoon and rainfall amount during RS, droughts and floods frequently occur over DPRK, resulting in the frequent occurrences of disastrous floods and agricultural failure.

Onset and Retreat of Rainy Season (O-RS and R-RS) are important parameters in the agricultural calendar in countries. Each country defined O-RS by different criteria because influence of synoptic systems on beginning, end and duration of RS is different in various regions. In addition, many regions over the world are expected to suffer from substantial climate modifications as a result of global warming (IPCC, 2013). These changes will affect the O-RS and R-RS which has become more irregular over the years for the past decades (Salack et al., 2011), making it difficult for farmers to plan for the seed planting, adjust to the length of the growing season and determine the harvesting period (Mugalavai et al., 2008). The immediate consequences would be the decrease of agricultural production and an increasing risk of hunger in developing countries. Therefore, the determinations of the O-RS and R-RS dates in various regions in particular in the developing countries of Asian Monsoon zone have become a focus for research.

O-RS is the beginning time of a rainy period of a year, when rainfall has become adequate for crop and vegetation growth; R-RS means the end of the rainy period, and Length of Rainy Season (L-RS) is the time period between the O-RS and the R-RS. In order to define quantitatively RS in mainland China, researchers used the climatologically pentad rainfall amounts, or the percentage (%) of total annual rainfall amounts, to determine the onset dates, ending dates, peak rainfall dates

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and lengths of the major RSs, (e.g. Wang and Ding, 2008; Zhan and Ren, 2016). Overall, the methods for determining O-RS and R-RS dates were classified into several categories according to Odekunle (2006) and others: (1) Intertropical Discontinuity (ITD)-rainfall model, (2) rainfall-evapotranspiration relation model, (3) percentage cumulative average rainfall model, based on rainfall data alone (Adejuwon, 2006), (4) wind shear model, (5) the Available Water Resources Index (AWRI), (6) model by using the daily rainfall data (Reiser and Kutiel, 2008), and (7) model based on outgoing longwave radiation (OLR) data (Garcia and Kayano, 2009).

Reiser and Kutiel (2008) conducted an in-depth research on definition of RS using accumulative precipitation from and till a day on which 10% and 90% of annual total precipitation is accumulated for determining O-RS and R-RS. Garcia and Kayano (2009) used the anti-symmetric feature in relation to equator outgoing long wave radiation (AOLR) to define rainy season and suggested a method of determining the O-RS date based on scale of spatial averages of the AOLR. Guenang and Mkankam (2012) studied O-RS, R-RS and L-RS by using observed precipitation in Cameroon during 1962–1993 and compared results to control simulations by four IPCC AR4 AOGCMs. Qiang and Yang (2008) made demarcations on O-RS and R-RS, and they found that the averaged O-RS date is in pentad 19 (the 1st pentad of April), while the R-RS is in pentad 34 (the 4th pentad of June) in south China. Laux et al. (2008) applied Fuzzy-logic method and daily precipitation data to determine the regional onset date of RS using linear discriminant analysis and linear regression analysis. These methods are potentially useful to judge whether the current onset of RS has already begun.

Researchers explained characteristics of RS and TR events over East Asia. Lau and Yang (1997) defined the RS standard as an average daily precipitation of 6.0 mm a day, but other researches showed that analysis of pentad rainfall is adequate to define beginning of RS (Hachigonta et al., 2007; Thomas, 1993; Qiang et al., 2008; Wang et al., 2010). Zhan and Ren (2016) analyzed climatological characteristics and temporal variation of O-RS and R-RS over East Asia during 1951–2009. They defined the RS by a pentad rainfall standard, constructed the regional average temporal series by using the weighted-average method, and analyzed the latitude–pentad profile of RS in East Asia including the Korean Peninsula. The work showed that the rainy belt slowly moves northward from 33°N to 36°N on the Korean Peninsula and the most rapid propagation of the onset time occurs around 36th pentad (25–29 June) in eastern China, followed by that in the Korean Peninsula.

Yao et al. (2008) showed that the summer precipitation has declined over the past 30 years in the Russian Far East and the northern part of DPRK. Lu et al. (2001) analyzed O-RS and R-RS of the Korean Peninsula, and the results showed that later O-RS onset is associated with the significantly weakened Asian monsoon, the lower-level westerlies are weakened and the atmospheric convection is suppressed, and the surface temperature is higher due to more net solar radiation flux and less latent heat flux at the surface. Jiang et al. (2008) indicated that, because of the East Asian summer monsoon begins later, summer precipitation decrease after the late 1970s in East China except for the Yangtze River basin. During the same period, Korean summer monsoon rainfall peak has delayed as well (Lee et al., 2010), though the second peak has advanced (Ho et al., 2003). Ding and Chan (2005) showed that the moisture transport coming from the Indochina Peninsula and the South China Sea plays an important role in supplying moisture for precipitation in East Asia after the onset of the Asian summer monsoon. Fang et al. (2017) analyzed the changing contribution rate of heavy rainfall to the rainy season precipitation in Northeast China, and they found that, although the contribution rate of heavy rainfall to the total rainy season rainfall showed a decrease during 1961–1979, it exhibited no significant trend during 1981–2013.

Recently, Ohba et al. (2015), Ma and Zhou (2015), Awan et al. (2015), Kim et al. (2016) and Liu and Wu (2016) also examined the long-term variation in rainy season and intense precipitation in East Asia Monsoon region over the past decades, and they all showed a complicated spatial and temporal pattern of summer extreme precipitation changes in the region.

Most studies on O-RS and R-RS in a few of countries or regions were performed on a limited number of stations or on relatively short time periods because of the lack of complete data series. Some researchers made detailed analyses of RS and intense precipitation individually for East Asian countries, but made no effort to investigate in details the long-term change in RS and TR over DPRK.

This paper made a first attempt to analyze O-RS, R-RS and L-RS over DPRK, and the synoptic circulation background at the beginning of RS. It also examined the climatological characteristics and long-term variation of TR over the country. The study will be help in deepening our understanding of the summer monsoon precipitation variability of the East Asia, and in coping with meteorological disaster risks under the changing climate condition.

2. Data, study area and methods

2.1. Observational data and definitions

Four observational data sets were used in the study: daily rainfall data from 181 stations during 1960–2007 (48 years), weather maps for RS in DPRK during 1960–2007 (44 years), El Niño (La Niña) records from TCC (Tokyo Climate Center), and daily precipitation and hourly maximum precipitation records for period 1969–2012. Station precipitation, typhoon data, TR data and weather maps were all provided by the HMBK (Hydro-Meteorological Bureau of DPRK). The TCC El Niño (La Niña) data are a little different from those by the Climate Prediction Center (CPC) of the United States National Ocean and Atmospheric Administration (NOAA) due to the different definitions of the NINO regions, with the TCC definition applying NINO 3 (5 N - 5 S and 150 W - 90 W) SST anomalies for El Niño (La Niña) events. All the precipitation data have been quality-controlled by the HMBK; however, in-homogeneities of the daily precipitation data probably caused by station relocations and instrumentations have not been examined and adjusted. Compared to those in other developing countries of Asia, the data inhomogeneities related to the station relocations may have not so serious in DPRK due to the relatively slow urbanization processes in the country. TR indicates much amount and heavy intensity of rainfall for a specified period. In DPRK, rainfall with an amount larger than 30 mm (50 mm, 100 mm and 200 mm) for an hour (3 h, 6 h and 12 h) was defined as TR. This definition is different from those in other countries. For example, China Meteorological Administration (CMA) defined the heavy rain event with precipitation amount larger than 16 mm (30 mm and 50 mm) for an hour (12 h and 24 h) as TR or rainstorm. The accumulated precipitation in RS events is almost equivalent to about 60 percent of amount of annual total precipitation in DPRK, and TR frequency during Jul–Aug accounts for 95 percent of total number of annual TR. In RS precipitation, the share of TR varies from region to region, with some regions like the Chongchon River basin reaching more than 80%. In South Korea, more than half of the annual precipitation occurs during summer, and more than 40% of the summer precipitation occurs during the Changma (Jangma) (Kripalani et al., 2002; Lu et al., 2001; Lu, 2002).

RS is regarded in DPRK as a sustained period of time when the rain frequently occurs within a year; In South Korea, however, RS is defined as “the rainy period with rain keeping falling for many days in summer” (Ryoo, 2001).

In this paper, O-RS is defined as the beginning time of RS when daily rainfall amount is over 50 mm for three continuous days, and it rains (rainfall > 0.1 mm/day) again within four days without clear weather. At the same time, the equivalent potential temperature at 850 hPa height keeps up more than 330 K over the area of more than two provinces of the country. If these conditions are met, RS in DPRK is considered to begin. Here, the two provinces are represented by two

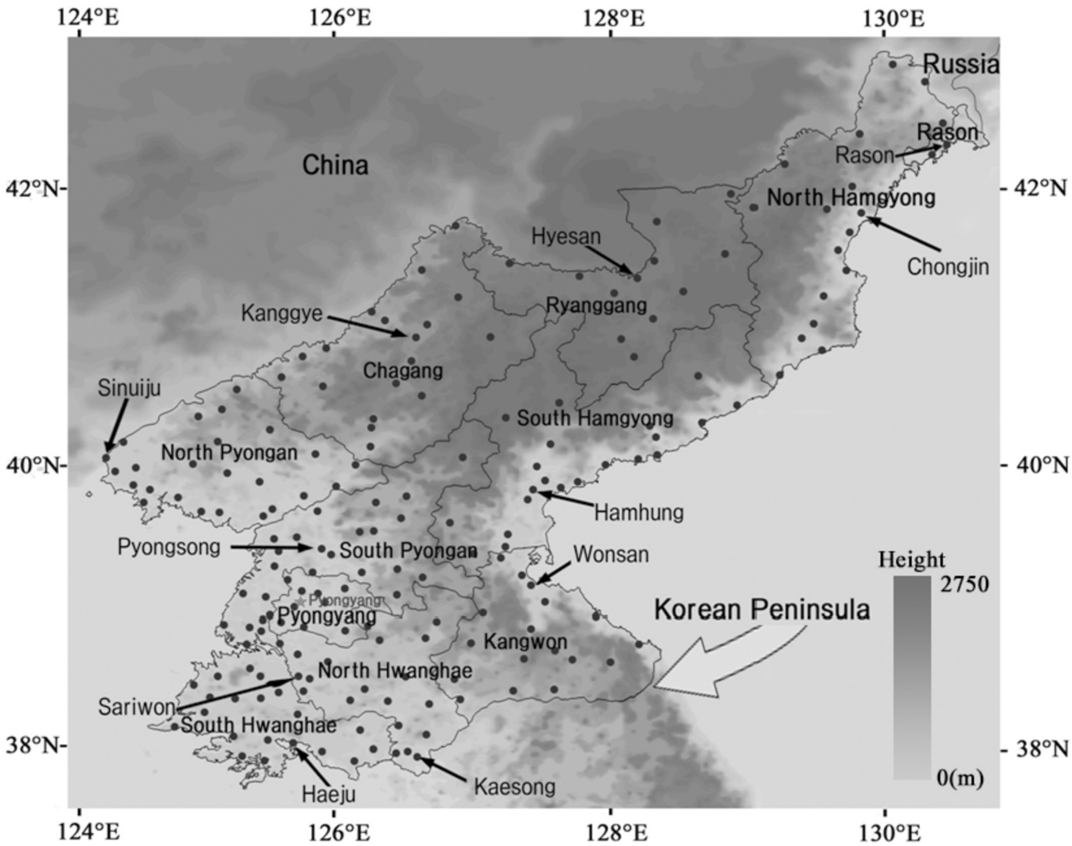

Fig. 1. Study area and the geographical locations of 181 surface observation stations in DPR Korea (37–43°N and 124–131°E). Boundaries between provinces are shown. The sites indicated by names and arrows are the eleven representative observational stations of the provinces.

respective typical stations which were chosen for use in PDRK weather operation (Fig. 1). R-RS, on the other hand, is defined as the end time of RS when daily rainfall more than 50 mm is no longer observed in the overall study area for three consecutive days, and the equivalent potential temperature at 850 hPa height is lower than 330 K over the area of more than two provinces. In this case, RS of DPRK is considered to be over. L-RS is the days from the O-RS to the R-RS.

2.2. Study area

The study domain, DPRK, is located in northern Korean Peninsula, between 37.7°N and 43°N and 124°E – 131°E (Fig. 1). It is encompassed by the Korean East and West Seas. Climate in the country is characterized by rainy and hot summer, and dry and cold winter, due to the influence of East Asian Monsoon. Wet and warm southerly airflows moves northward during summertime, bring moisture and heat to the study area.

The geographical location of the stations and terrain conditions of the study area are shown in Fig. 1. Most of the study area is mountainous, usually are characterized by a series of horn gates opening to the southwest and south, which benefiting occurrences of TR events (e.g. northern South Pyongan and southern North Pyongan). Representative stations highlighted in Fig. 1 are generally belonging to the provincial capitals or municipality cities, which have the best data quality and the longest records of observation. Though most of the rest stations also keep a very good precipitation record during the study period, some of them have missing values. The missing daily records, however, account for less than 2% of total observations, and will not have a significant impact on the analysis results.

The average distance between stations in the study area is less than 30 km. The densest distributions are seen in Pyongyang and South Pyongan, and the density of stations is the lowest in Ryanggang and North Hamgyong.

2.3. Circulation patterns of RS

The O-RS is characterized by a typically abnormal circulation fields. Due to the expansion of ridgeline of the West Pacific Subtropical High (WPSH), the warm and moist air flows from the Indian Ocean and the South China Sea to the Korean Peninsula and Japan through southern China and the Yangtze basin, forming a front in boundary with air from high latitude, which is called as "Jangma (DPRK)/Changma (South Korea) Front". The summer RS in DPRK is generally consistent with "Jangma/Changma".

To understand the circulation patterns for O-RS, we analyzed annual mean-500 hPa geopotential height in upper level and mean-850 hPa barometric distribution in low level for five days before the beginning time of Jangma/Changma or RS, respectively. All 5-day mean weather maps for 1960–2007 were used to analyze the circulation patterns. Circulation types of the five days before the beginning of Jangma over DPRK were divided into two patterns. The first pattern begins with the condition that the WPSH moves northward and westward significantly. These cases accounts for 80 percent of the total (Fig. 2a). This pattern is characterized by the strengthened northwestward expansion of the upper-layer WPSH, a large cyclone area over the western Bay of Bengal and the Indo-China Peninsula, a blocking high over the west of Ural and the Far East of Russia, and a long-wave trough line in the central Siberia and cold air coming down continuously southward from the west of the Baikal Lake (E 104°–109°, N 51°–55°). On the other hand, along the western boundary of the strengthened WPSH, warm and moist marine tropical air mass flows toward northeast, forming Jangma-Front and the summer RS begins over study area. At the surface, a cyclone strongly develops in North China and the western Yellow Sea, forming a pressure distribution with east high-west low pattern.

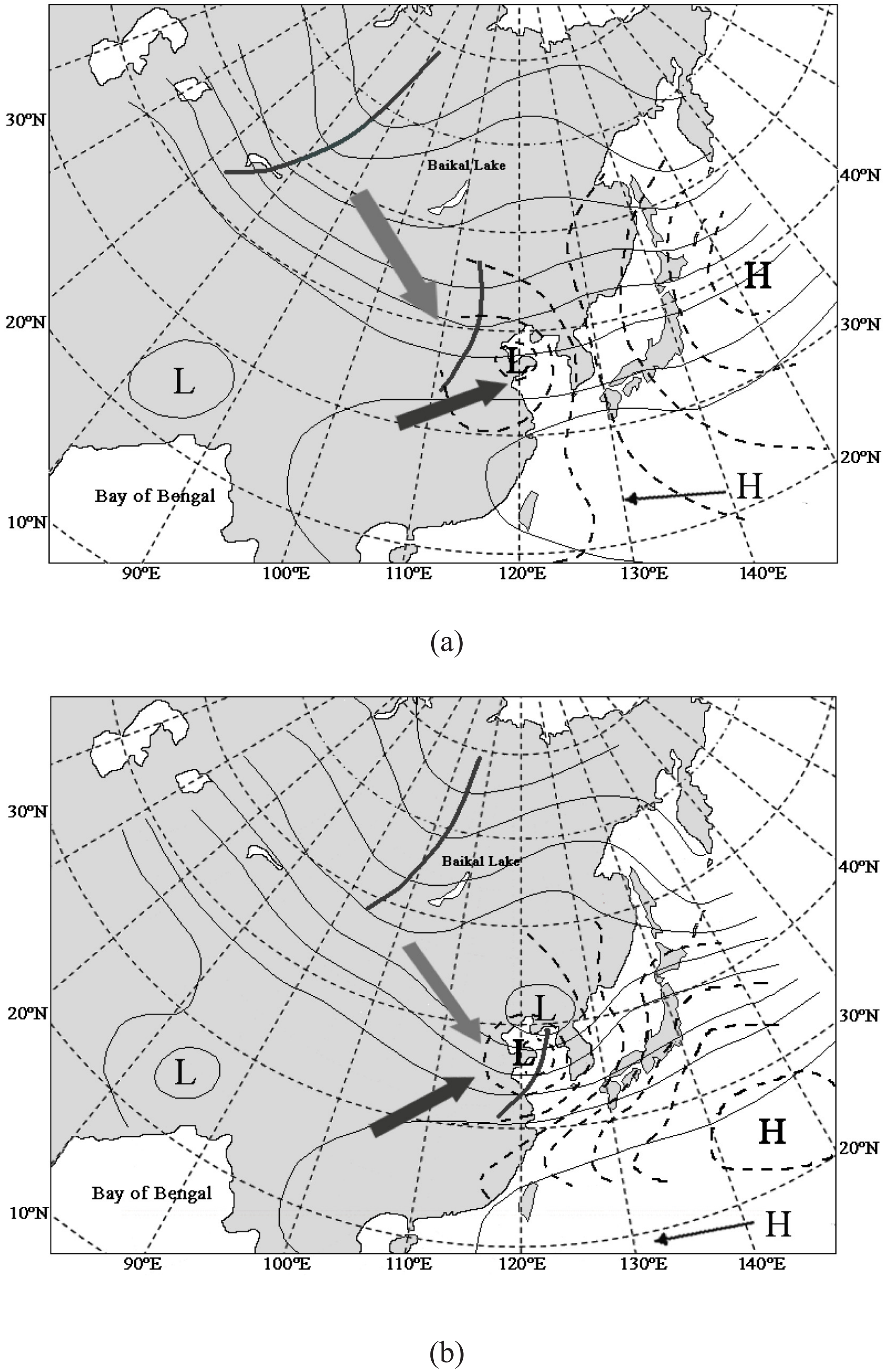

Fig. 2. Two circulation patterns for onset of rainy season (O-RS). a: first pattern, b: second pattern, solid line: 500 hPa geopotential height (unit: 8gpdkm), dash line: 850 hPa geopotential height (unit: 8gpdkm); thick and light grey arrow: cold air, thick and dark grey arrow: warm air, thin arrow: moving direction of the Western North Pacific High ridge.

The second pattern develops without the characters as mentioned above, and these account for 20 percent of the total cases (Fig. 2b). In this pattern, the WPSH is weaker than the first pattern, and it is located on south of 25°N with no closed center. It extends slightly northward compared to the first pattern, but expands to the west a little bit further. The local cyclone is located over the western Bay of Bengal and the Indo-China Peninsula, the blocking high over the west of the Ural leans to more eastward than the first pattern, and the long-wave trough is located over the west of the Baikal Lake. At the surface, the cyclone in North China strengthens relatively. In the second pattern, the further expansion of WPSH makes the northeastward movement of warm and humid airflow to be weaker, and the rainfall during RS in the study area is lower and L-RS is shorter than those in the first pattern.

Therefore, the synoptic characteristics at O-RS are an obvious movement of WPSH northward to the north of 25°N and westward to the west 150°E, with the ridgeline swing between 25°N and 27°N; at the same time, jet stream axis of high level over the longitude zone near DPRK moves to the north of 35°N-37°N.

With the same procedure, we also analyzed annual mean-500 hPa geopotential high in upper level and mean-850 hPa barometric distribution in low level for five days after the end of Jangma respectively, and identified the dominant patterns of the DPRK R-RS.

In the following sections of this paper, we analyzed the temporal variations of the RS indicators and TR events over the study area, including the decadal means and the long-term trends of the indicators, in addition to their climatological characteristics for the entire periods of observations available. Statistical significance of the trends of all climatic elements and indicators were tentatively examined using T-test method.

3. Results

3.1. Characteristics and variation of O-RS and R-RS

RS usually lasts from June to August in the study area. When the first rain of RS occurs, the Yangtze River cyclone usually lies over the north of central DPRK, and the Yellow River cyclone moves northeastward. In view of characteristics of air masses, the equatorial air mass is widely distributed over south of the Yangtze River and the subtropical air mass occupies up to 40°N. Table 1 shows the statistical values of RS during 1960–2007. Regarding the O-RS dates, it is 18th of June (1990) in the earliest case, 29th of July (2000) in the latest, and 5th of July in average. If it began within one week of the average date, then O-RS was considered as normal.

The mean R-RS is on 25th August, however, the earliest date (1972) is in early July and the latest one (1964) appears in the mid of September. 1972 witnesses the earliest retreat date on 6th July, and it is an extremely anomalous case. Usually, the retreat date occurs in the end of August or early September, though the Typhoon processes passing through East Asia including DPRK occasionally can delay the retreat date to early or even mid-September. If the RS began within June, it could be called an early RS; if it ended in September, it could be called a late RS. The longest L-RS occurred in 1966 and 1990, both reaching 76 days, and the two shortest L-RS were in 1972 (3 days) and in 1991 (16 days) (Fig. 3). The average L-RS is 54 days.

Table 1
Statistical values in O-RS and R-RS.

Statistical indicator	Value
Mean of O-RS	5 July
Mean of R-RS	25 August
Standard deviation of O-RS	8.89 d
Standard deviation of R-RS	13.06 d
Correlation coefficient between O-RS and L-RS	−0.60 (99.9%)
Correlation coefficient between R-RS and L-RS	0.84 (99.9%)

Years 1966 and 1990 are the cases of early O-RS. The ridgeline of WPSH is located on north of 25°N well before July. The circulation belongs to the first pattern of O-RS. In 1991, when a late O-RS was observed, WPSH hadn't developed into a closed center and it hadn't moved northward. The high stayed between 20°N and 25°N for almost 50 days. The O-RS in 1972 was normal, when the weakened WPSH hadn't had a closed center as well but it extended northwestward more than normal; however, WPSH retreated to the east of 150°E on July 6, leading to an unusual early end of RS. In the study, we considered these cases as the second pattern of air circulation.

Table 2 shows the decadal mean values of O-RS, R-RS and L-RS from 1960 to 2007. It is clear that the decadal mean of O-RS delays gradually, R-RS becomes earlier in some extent and the L-RS has an overall downward trend. Therefore, the characteristics of RS have changed obviously over DPRK during the past decades. The linear trend of O-RS was 1.9day/decade, indicating a tendency for the O-RS dates to be gradually delayed during the study period. On the contrary, R-RS dates are getting earlier with a decreasing rate of −2.7day/decade. As a result, L-RS is getting shorter with a trend −4.7day/decade. All the above trends are statistically significant at the 0.10 confidence level, but only the trend for L-RS is significant at the 0.05 confidence level.

3.2. TR events in RS

We analyzed the spatial and temporal characteristics of TR events, and their relations with different weather processes in the study periods. The most frequent weather processes accompanying TR events are cyclonic weather (~35% of the total TR events), followed by typhoon processes (~30%) and frontal weather (~22%), with the others only accounting for less than 13%.

3.2.1. Change in number of TR events

Annual mean number of TR events more than 100mm/6 h and more than 200mm/12 h for 181 stations over DPRK during 1969–2012 is shown in Fig. 4. The annual mean number of TR events less than 6 times accounts for a much proportion before 1993, and most of the years have more than 6 times after that year. Therefore, more frequent TR events occurred after 1993. Fig. 5 shows decadal mean of TR frequencies (R_{6h}≥100 mm, and R_{12h}≥200 mm) for the period 1974–2012. It can be seen that the annual mean of TR events (R_{6h}≥100 mm) is 6.2 times, and it increased from 4.2 times for 1974–1983 to 7.4 times for 2003–2012 (Fig. 5a and Table 3). Fig. 5b shows that the annual mean of TR (R_{12h}≥200 mm) is 0.9, and it also significantly increases since 1974, with 0.6 for the first decade to 1.2 for the last decade. Hence the extremely intense rainfall for R_{12h}≥200 mm almost doubles from the first decade to the last decade during the period 1974–2012. Linear trends of R_{6h}≧100 mm and R_{12h}≧200 mm are 0.67/decade and 0.2/decade, respectively, and the trends are all significant at the 0.05 confidence level.

The extremely TR event with precipitation above 300mm/18 h occurred only once (2012/07/30); and TR events with precipitation beyond 200mm/12 h and 100 mm/6 h occurred more frequently, reaching 38 times and 271 times respectively. The annual mean of TR events ranges from 0.1 (beyond 270mm/18 h) to 6.2 (beyond 100 mm/6 h). Monthly mean TR (R_{6h}≧100 mm and R_{12h}≧200 mm) frequencies and percentages during the study period are shown in Table 3. It is obvious that all TR events occurred during summertime (June to September), and they appeared most frequently in August especially for TR (R_{12h}≧200 mm) which amounts to 47.4% of total. Table 4 also shows that the months with high frequency of TR events, in descending order, are August, July, September and June, which is consistent with the fact that precipitation amount and rain frequencies are mostly concentrated in mid-summer of July and August.

Typhoon processes across East Asian region including the Korean Peninsula are the main reason why many TR occur more often in September than in June. In 2002, Typhoon Rusa produced a record

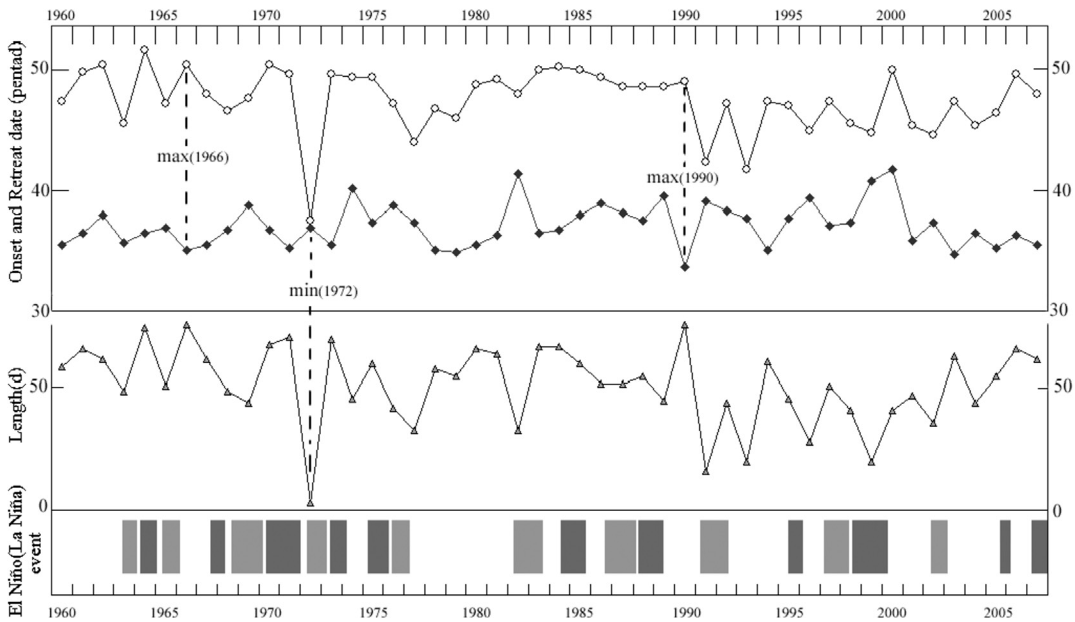

Fig. 3. Onset date, retreat date and the length of rainy season (O-RS, R-RS and L-RS) over the study area. Solid square: O-RS date; open circle: R-RS date; triangle: L-RS. Light grey: El Niño event, and dark grey: La Niña event, at the bottom.

Table 2
Decadal mean values of O-RS, R-RS and L-RS in the study area.

Decade	Onset date	Retreat date	Length (d)
1960–1969	7/02	8/30	59
1970–1979	7/05	8/23	49
1980–1989	7/06	9/03	59
1990–1999	7/07	8/20	44
2000–2007	7/07	8/23	47

rainfall (870.5mm/d) in Gangneung at the foot of the Taebaek Mountain range over South Korea; this was the maximum record of precipitation in the country (Lee and Choi, 2010). According to the analysis of pressure systems over the study area, the TR events of Jul–Aug are mostly related with the temperate cyclones and front, but those in the end of Aug and early Sept occur mainly due to influence of typhoons or tropical cyclones.

It is worth noting that TR frequencies have a low correlation with the O-RS, R-RS and L-RS. The shortest L-RS is in 1972, and TR (R_{6h}≥100 mm) occurred 6 times, and TR (R_{6h}≥100 mm) occurred 10 times during the longest L-RS of 1990. The TR occurrences are therefore irregular in some extent. The correlation between L-RS and TR (R_{6h}≥100 mm) frequency is the highest, but it reaches only 0.18, showing the possibility that the longer L-RS somewhat benefits the more frequent occurrence of the low-grade TR events.

3.2.2. Spatial difference of TR events

Fig. 6 shows that the frequent TR events and large TR amount are generally in the northwest or the mid-basin of the River Taeryong and the River Kuryong, including North Pyongan Province, and the southernmost parts of the study region. The most frequent occurrences of TR (R_{6h}≧100 mm) are in Pyonggang, Kosong, Kumkang, Taechon, Unsan, Kusong, Tokchon, Maengsan, Jangpung, Chorwon and Tongchang, and most frequent occurrences of TR (R_{12h}≧200 mm) are in Chorwon, Unsan, Tosan, Huichon and Kosong. The distribution of the several TR centers and their topographic conditions are shown in Fig. 6a.

DPRK belongs to monsoon climate, with the direction of summer prevailing flows being southwest and southeast. The three main rainfall centers with high frequent TR all lie to the windward slopes of mountain range for the summer southwesterly and southeasterly. Particularly, regions with most frequent TR are usually surrounded by high mountains on three sides, and other side is 'V-shaped' terrain just like a horn gate. Upper stream and midstream of the River Taeryong and the River Kuryong have a couple of such 'V-shaped' terrains. These rivers are tributaries of the River Chongchen, flowing through south of

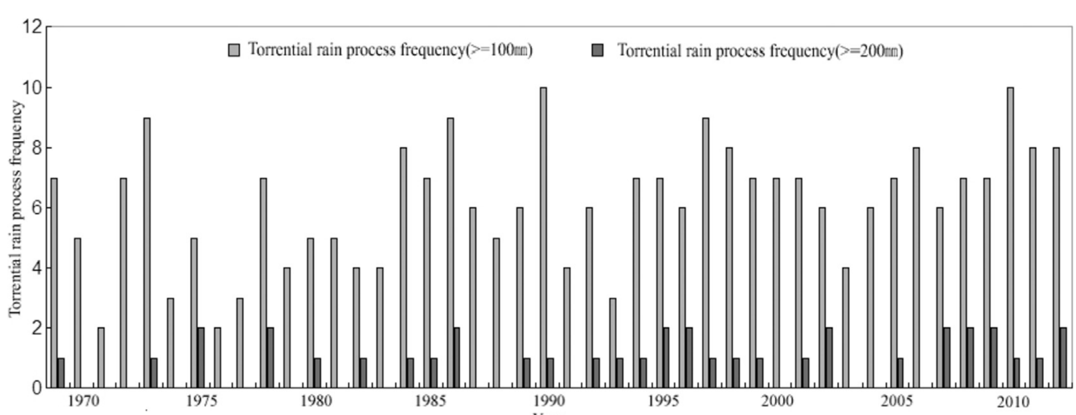

Fig. 4. Annual mean frequencies (occurrences) of torrential rain (TR) events (> =100 mm/6 h and ≥ 200mm/12 h) during 1969–2012 in the study area.

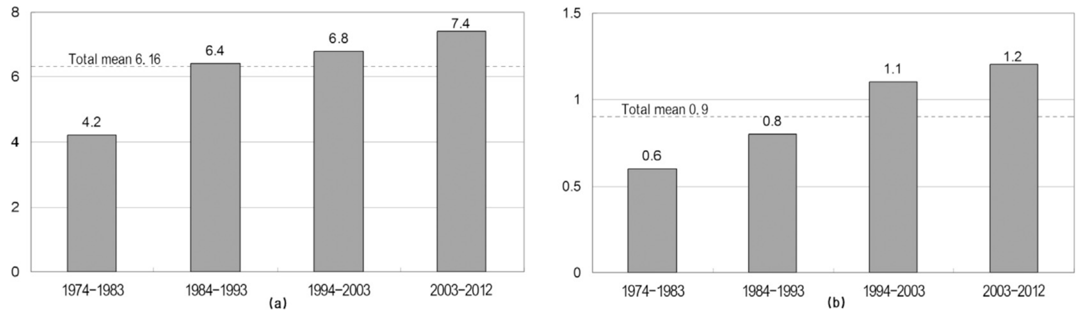

Fig. 5. Decadal mean numbers of occurrences of torrential rain (TR) events for the last 4 decades in the study area (a): R_{6h}≥100 mm, (b): R_{12h}≥200 mm.

Table 3
The number of different categories of TR events in DPR Korea during 1969–2012.

Temporal scale (hours)	Classification (mm)	Process number	Annual mean
6	R≧100	271	6.2
12	R≧200	38	0.9
18	R≧200	36	0.7
	R≧220	17	0.4
	R≧270	4	0.1
	R≧300	1	

Table 4
Monthly TR event frequencies and percentages in DPR Korea during 1969–2012.

Temporal scale	Classification (mm)	Jun	Jul	Aug	Sept	Total
6 h	R≧100	14	101	114	42	271
		5.2%	37.3%	42.1%	15.5%	100%
12 h	R≧200	2	12	18	6	38
		5.3%	31.6%	47.4%	15.8%	100%

TR frequent regions (Taechon, Unsan, Kusong and Tongchang) in North Pyongan Province, and the high-frequent TR regions lie to the southern slope of the Jekyuryeng Mountain range. The Tokchon and Maengsan regions also lie to the upper stream of the Taedong River, and the Pukdaebong and the Myohyangsan Mountain ranges seat respectively east and north of these regions, with southwest being opened horn gate terrain, benefiting occurrences of summer TR. Chorwon, Pyonggang, Kumkang and Kosong of Kangwon Province also became known as habitual TR regions, with the Ahobiryong Mountain range stretching to the west, the Chorryong Mountain range on east, and the southwest opened to the Ganghua Bay. In addition, TR events caused by typhoons occur more frequently in Kangwon region than those in other regions. In this case, WPSH often expands to southern DPRK, low level jet stream axis lies north of 35°N, and the moist and warm air flows can easily enter the study area, making TR events more frequently to occur.

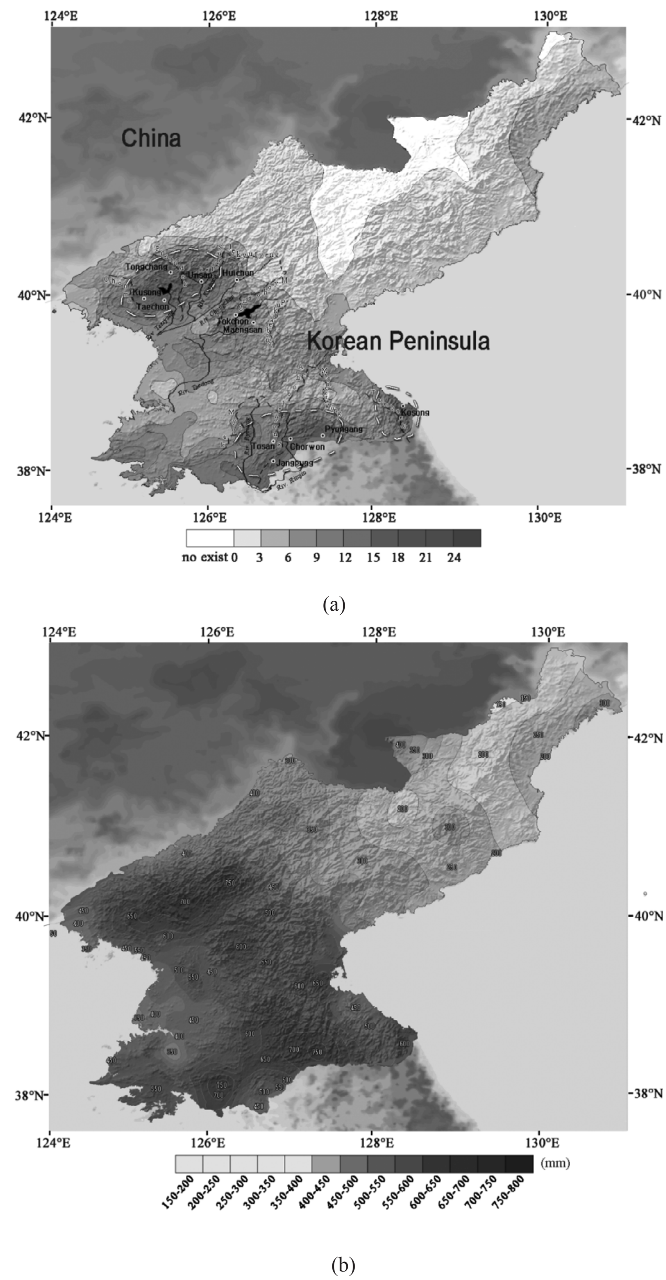

Fig. 6. High-frequency TR regions in major river basins (a), and annual mean frequencies (occurrences) of TR events and precipitation distribution (b), over DPR Korea for period 1969–2012. Solid line: river; dash line: watershed.

4. Discussion

4.1. Differences between this study and that reported in South Korea

In many case, the long-term variations of O-RS and R-RS in DPRK are consistent with the previous studies for East Asian region (e.g. Kitoh and Uchiyama, 2006; Endo, 2011; Zhan and Ren, 2016). However, Choi et al. (2008) showed that R-RS in South Korea was delayed from early September to mid-September for 1973–2007, which is somewhat different from our result for the study area. The possible cause for the difference may mainly result from the different definitions of O-RS and R-RS. Ryoo (2001) analyzed the results of the prior studies on RS in South Korea and found that the definitions for RS are different among researchers. However, a unified definition does not exist. A representative definition of RS recommended by Korean Meteorological Administration (KMA) is as follow.

Onset date: At a specified region, (a) the duration of rainfall is more than 3 days, and (b) the quasi-stationary (Changma) front is located over the whole South Korea; Retreat date: the duration of non-precipitation exceeds three days and the quasi-stationary fronts leave northward.

Based on this and the one given in this paper, we found three main differences in the definitions and meanings of RS in the study area and South Korea.

(1) Regional classification: KMA announces O-RS and R-RS dates by region (Jeju, Mokpo and Seoul) (Ryoo, 2001). However, this study considers the first day of RS in any area as the onset date of the national RS, and the latest day as the retreat date. These are the most notable difference. Some researchers (e.g., Lee and Kim, 1983) from South Korea have also suggested considering the country RS to begin (end) when any area of Jeju, Mokpo and Seoul witness the beginning (retreat) of RS.
(2) Circulation pattern: KMA regards the non-precipitation (the mid-break of RS) due to WPSH expansion to cover the whole South Korea as R-RS. In this study, although Jangma Front moves to north of 45°N in the early August to mid-August, resulting in a mid-break of RS, we probably still consider the period (it is called "late Jangma" in DPRK) as RS because the weakened Jangma Front may move southward and precipitation may be observed again. The length of the mid-break in the study area is also much shorter than that in South Korea due to the differentiated time periods controlled by WPSH, and this may be the reason why the period from late-August to mid-September is not considered as part of RS in South Korea.
(3) Precipitation indicators: In the definition of O-RS, we used cumulative precipitation amount of more than 50 mm for 3 days in study. However, three consecutive days with precipitation are used in defining the beginning of O-RS in South Korea.

We compared the results of the study with those by using the criteria in South Korea (Ryoo, 2001) for the period 1961–2000 (Fig. 7). It is clear that the R-RS dates in this study are usually 16 days later than those obtained by KMA. In the study, the precipitation condition for O-RS date is similar to that in South Korea, and the difference of O-RS between DPRK and South Korea is not so large.

In other words, under the same atmospheric circulation, the difference between this study and KMA is caused by the northward migration of Jangma Front from Jeju Island in South Korea to the southern region of the study area. The almost same onset dates between regions in 1990 mean that Jangma Front moved very rapidly to the north. In addition, the difference of retreat dates, 33 days on average, reflects the usual time period taken for the Jangma Front to move southward again through the study area after it leaves South Korea. Mean L-RS in this study is 17 days longer than that reported in KMA, in spite of the fact that it was much shorter in 1972, 1991 and 1993 (Fig. 7b), when Jangma Front had been stagnant for a longer period in south of 25°N, and had shifted to the southeast without any northward jump of WPSH. On contrary, the difference of L-RS between the two regions is beyond 60 days in 1973, with the mid-break of RS in the study area relatively longer because Jangma Front stays in Northeast China for an unusually long time after it crosses the Korean Peninsula.

It should be pointed out that different definitions of climatological terms are usually applied for different countries and regions. This would be mainly related to the varied climatic and geographical conditions, and also to the relatively independent studies by researchers in different countries. This may result a difference among the analysis results of climatological features. However, the long-term climatic change and variability of rainy season and torrential rain events as analyzed in this paper would not be affected by the different definitions used in the two countries. What is important is that we have used consistent terms throughout the study, and this would guarantee the reliability of the analysis results of the long-term rainy season and terrestrial rain variation.

4.2. Mechanisms of TR and RS variations

As shown in Fig. 4, the annual extreme precipitation events significantly increased during the analysis period, with the mid-1990s as a shift point. Especially, TR ($R_{6h} \geqq 100$ mm) has grown sharply by about 1.5 times since 1984, compared with the pre-period (1974–1983) (Fig. 5). These results are consistent with the results of Choi et al. (2008) and Jung et al. (2002, 2011). Sun et al. (2006) showed that the precipitation amount and intensity of annual rainstorms had a detectable upward trend in Northeast China for four decades of last century. The similar changes in extreme precipitation over the past decades in eastern China were also observed (e.g. Zhai et al., 2005; Zhang et al., 2009; Ren et al., 2010).

The monthly frequencies of TR ($R_{6h} \geqq 100$ mm and $R_{12h} \geqq 200$ mm) in August are bigger than July, as shown in Table 4. This result is also comparable to the analysis by In et al. (2014). They also found an increasing trend of precipitation amount and precipitation frequency in August from 1973 to 2010 over South Korea, which may have caused the average frequencies of TR to rise in the last two decades.

The main cause of the regional difference in distribution of TR events over DPRK is related to the orographic effect. In particular, Kosong, Taechon, Unsan, Tokchon, Maengsan and Chorwon regions (Fig. 6) are located on the windward side of the southwest or southeast wind during the summer monsoon season. The spatial characteristics of TR due to the orographic effect in the Taebaek Mountain Range was also seen in South Korea (Lee et al., 2012), where the most frequent occurrences of the monthly maximum precipitation in the Gangneung area could be caused by orographic effects. Choi et al. (2008) further showed that the statistically significant increasing trend of TR for 1973–2007 was centered on the Taebaek Mountain Range, which include Kosong and Kumkang regions of DPRK.

The long-term changes in RS and TR in DPRK may be related to the following factors and mechanisms. We analyzed the correlation coefficient between O-RS and R-RS dates over DPRK and El Niño events. Results show that the correlation coefficients of O-RS and R-RS dates with El Niño events of preceding winter are −0.31 and 0.23, respectively, indicating that mean SST anomalies in the equatorial Pacific significantly influences RS in DPRK, with the stronger El Niño event followed by the longer RS of next summer in DPRK. A strong La Niña event appeared during spring 1970-winter 1971/72, and the L-RS of 1972 in DPRK was the shortest (3 days).

Different El Niño events may have different effects on the location and strength of WPSH in summer (Wang et al., 2012; Li and Wang, 2012). It is possible that the upward movement of the air by rising SST in the eastern equatorial Pacific due to the strongly maintained EP-El Niño event during preceding winter not only changes the normal Walker Circulation but also weakens Hadley Circulation which otherwise transports enormous thermal energy from the equator to the subtropical region in the western Pacific. The suppressed circulation forms a pattern with Sea Level Pressure (SLP) higher in the east than that in the west in zones around 30°N, a dynamical condition which makes WPSH to strengthen and its ridgeline to expand northwestward, benefiting the northward move of warm and moist airflow to invade into northeastern Asia along the western boundary of the WPSH. In the case of CP-El Niño, a different pattern appears, in which SLP in the central part is higher than that of the west in subtropical area, and the pressure gradient is steeper than that in the first pattern, which gives the possibility that WPSH ridge more shifts to the north. As a result, RS in the study area begins usually earlier and lasts longer than that in case of EP-El Niño event.

In La Niña, the atmospheric circulation system is reversed, and it

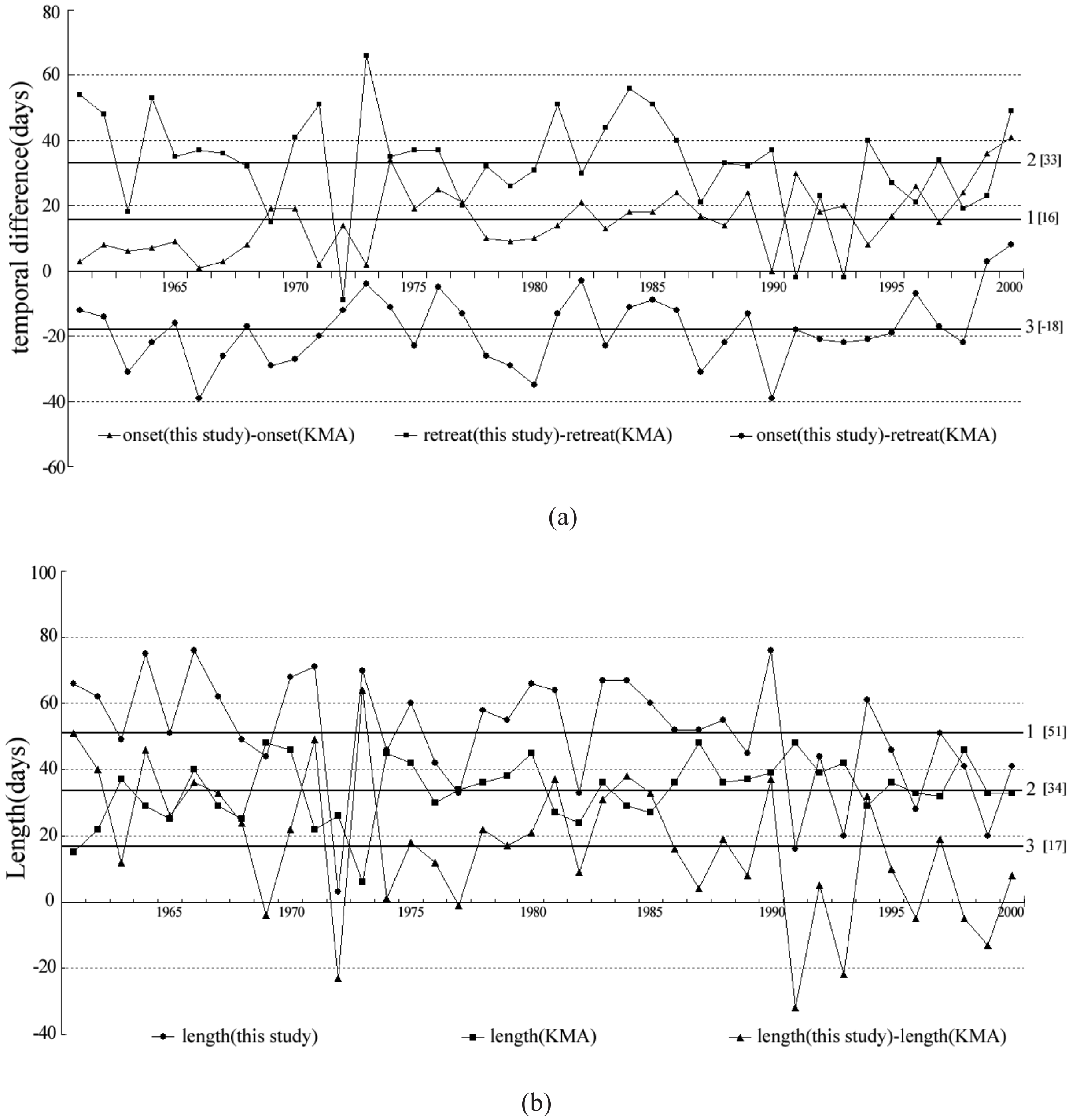

Fig. 7. Differences of onset, retreat and length of rainy season (O-RS, R-RS and L-RS) between this study and KMA. a-1 (triangle): onset (this study) - onset (KMA), a-2 (square): retreat (this study) - retreat (KMA), a-3 (circle): onset (this study) - retreat (KMA)); b-1 (circle): average for L-RS of this study, b-2 (square): average for L-RS of KMA, b-3 (triangle): average difference of L-RS between this study and KMA. Values in square brackets on rights of the curves are mean order number of pentads. KMA: Korean Meteorological Administration.

therefore benefits a later and shorter RS in the study area. This mechanism also satisfactorily explains the anomalously short RS (3 days) in DPRK in 1972 summer after a strong La Niña in 1970/71. We found that, on average, O-RS was 4.4 days earlier and L-RS 5.5 days longer after the CP-El Niño event than they were after the EP-El Niño, and O-RS with La Niña was delayed by 5.6 days and L-RS decreased by about 7 days.

Cai et al. (2003), Jin et al. (2005), Li et al. (2010), Wang et al. (2012), and Li and Wang (2012) all reported the changes of WPSH and East Asian climate under different patterns of El Niño events, but they had not discussed about the conceptual relationship of the patterns with O-RS and L-RS variations in East Asia in particular in DPRK. Other factors and processes may also affect the RS and TR over the country. Among others, mid-latitude trough and western Pacific typhoon would be important, and they deserve serious consideration in the future studies.

In addition, TR may be also associated with aerosol emission in eastern Asia. During RS, the study area is often affected by the Yangtze River cyclone and Yellow River cyclone. These cyclones occur 8–9 times a year in the Yangtze River and Yellow River basins and the Bohai Sea in mainland China, and move eastward to the study area. The currents and clouds in the cyclones contain high concentration of aerosols with their generation and development, which may play an important role in formation and development of TR as cloud condensation nuclei (CCN), facilitating or weakening the rainstorms in the Korean Peninsula when combined with water vapor. The microphysical mechanism of aerosol in clouds and precipitation is complex. However, it may act to suppress precipitation in shallow clouds, and to encourage precipitation of rain clouds by the vigorous convection and the nucleating process of large water droplets in warm and moist thick clouds (Qian et al., 2003; Rosenfeld et al., 2008; Stevens and Feingold, 2009). The extremely intense rainfall of RS in the study area may be affected in some extents by these eastward-moving cyclones. During the study period, the annual precipitation caused by the temperate cyclones indeed shows an increase at a rate of 22.5mm/decade (90% confidence level), which may be in certain extent related to the aerosols effect, in spite of the fact that there is a large uncertainty in our understanding of this issue.

The rapid regional warming should also be considered (Alexander et al., 2012). The upward trend of TRs in DPRK may be the response of regional climate to the strengthening of the hydro-cycle induced by climate warming. Our analysis (not shown in this paper) showed that the rate of temperature increase in DPRK since the late-1970s reached 0.35 °C/decade, which was higher than global (0.17 °C/decade), northern Hemispheric (0.30 °C/decade) and Asian (0.28 °C/decade) (Jones and Moberg, 2003) and mainland China (about 0.25 °C/decade) (Ren et al., 2012) averages during same period. The increasing rate of mean temperature during RS period (7/5–8/25) in DPRK is about 0.25 °C/decade. The more rapid warming generally occurred in the lower atmosphere, leading to a steeper temperature lapse rate and a more intense air convection motion, which may in some regions cause an increasing TR.

The increasing difference of warming between the oceans and the continents in summer should cause the stronger East Asian summer monsoon, leading to more frequent and intense TRs in DPRK. However, many studies showed a weakening summer monsoon during the past decades, in particular in the period since late 1970s (e.g. Wang, 2001; Wang and Ding, 2008; Jiang et al., 2008; Ren et al., 2015). The weakening East Asian summer monsoon actually decreased the precipitation and intense rainfall of summer in northern China (Ren et al., 2000; 2015; Zhai et al., 2005; Ding et al., 2008). The causes of the change in East Asian summer monsoon have not been well understood, but it has been related to the increase in the atmospheric aerosols in East Asia in particular in eastern China (Rosenfeld et al., 2008; Ding and Ren, 2008). If so, the observed change in occurrence of TR events in the study area and northern China may not rule out the possibility of influence of global and regional warming on summer monsoon of East Asian and intense precipitation of DPRK. Further studies of attribution using climate models may help on this regard.

Whatever the causes of the observed change in RS and TR events, it would be important for evaluating the risks of the climate change and variability to agriculture and economic development in DPRK. As seen above, annual TR events showed a significant increasing trend, in spite of the fact that L-RS was getting shorter. This implies that the agriculture and water resources management are facing a larger risk of severe floods during summer, and effective measures have to be taken to copy with the potential disasters.

The results reported here are also relevant to researchers who have long focused on observed and modeled studies of precipitation change and variability in East Asia including mainland China and Japan with DPRK left blank due to the availability of high-quality data. However, there are still a couple of issues which need to be tackled in the future. These include, among others, the difference between DPRK and neighboring countries in definition of TR, the studies of change of the other extreme precipitation events in DPRK, the investigation of the possible causes and mechanisms of the observed decadal variation and long-term trends of RS and TR events in the country, and the modeling and projection of the DPRK precipitation and torrential rain processes in decades to come under the anthropogenic global and regional climate change.

5. Conclusions

There is a relatively dense observational network consisting of 181 meteorological stations with at least 44 year records in DPRK. Daily precipitation data of these stations were used to analyze onset, retreat and length of rainy season. Also analyzed were the climatological characteristics and long-term variations of torrential rain events over the past decades. The following conclusions can be drawn from the analysis:

(1) Onset, retreat and length of rainy season in DPRK showed obvious inter annual and decadal variability. Onset of rainy season was associated with the northwestward move of western Pacific Subtropical High to the area north of 25°N and west of 150°E, with the high ridgeline vibrating between 25°N and 27°N.
(2) The linear trend of onset of rainy season was 1.9d/decade during 1960–2007, indicating a tendency for onset of rainy season to be gradually delayed, and retreat of rainy season was getting earlier with a downward trend of −2.7d/decade. This had led to a shortening length of rainy season at a rate of −4.7d/decade.
(3) Torrential rain events and rainy season precipitation amount had clear regional differences. In the southwest and northwestern regions of the study area, torrential rain events were the most frequent and precipitation also was the highest, and these were attributed to the orographic influence benefiting occurrences of summer torrential rain.
(4) Annual frequency, intensity and amount of torrential rain kept increasing over DPRK during the last four decades. The annual number of torrential rain events with amount of precipitation more than 100 mm/6 h linearly increased from 4.2 times to 7.4 times in the period 1974–2012, and the annual number of extremely intense torrential rain events more than 200mm/12 h also significantly increased during the same period.
(5) Influences of El Niño (La Niña) on rainy season might not so straight, with the rainy season after Central-Pacific El Niño events beginning earlier and lasting longer than that in case of Eastern-Pacific El Niño event. After La Niña of preceding winter, a later and shorter rainy season usually resulted. The possible impacts of large scale anthropogenic emissions of aerosols and greenhouse gas on onset and length of rainy season had not yet been determined.

Acknowledgements

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