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Start and End Dates of Rainy Season and their Temporal Change in Recent Decades over East Asia

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Abstract

This paper analyzes climatological characteristics and temporal variation of the start and end dates of the rainy season over East Asia using a daily precipitation dataset for the time period 1951–2009. The rainy season is defined by a 5-day rainfall standard, and the regional average time series is constructed by applying the weighted-average method. Results show that the rainy season starts later, ends earlier and lasts shorter from southeast to northwest. In spring, the rainy belt slowly moves northward from 30 to 33°N in China and from 33 to 36°N on the Korean Peninsula and Japanese Islands. From 1951 to 2009, the rainy season generally began earlier in China but later in Korea and Japan, and it ended earlier at latitudes north of 35°N and later south of 35°N. The region-averaged start and end dates of the rainy season in the study region insignificantly advanced, and the duration of the rainy season insignificantly increased from 1951 to 2009. The rainy season duration slightly decreased in the Russian Far East and in northern and western China, and significantly decreased on the Korean Peninsula and the southern Hokkaido Islands, though it obviously increased in the Yangtze–Huaihe River Basins.

Keywords East Asia; rainy season; precipitation; climatology; climate change

1. Introduction

The temperate zone of East Asia is located on the east bank of the mid-latitude part of Eurasia. Thermal differences between the oceans and lands have produced a typical monsoon climate in this region, characterized by abnormally hot and rainy summers, and cold and dry winters (Ren 1991). By analyzing

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the climatological characteristics of this monsoon zone, we can understand the inter-annual and longer-term (decadal to multi-decadal) variations better in the regional precipitation, and the connections and differences between different regions, and thereby lay a foundation for climate prediction and simulation studies of temperate East Asia.

Seasonal precipitation variations are mainly affected by the seasonal movement of the monsoon rain belt in this region (Qian et al. 2002; Zhao and Zhou 2006). The characteristics of East China's rainy season have been extensively investigated (Chen et al. 1984; Ding 1992). Most of these studies have linked the outbreak, movement, and attenuation of the rainy season in eastern China to the summer monsoon in East Asia (Zhu et al. 2000). In eastern China, the rainy season begins in early spring (between late March and May) to the south of the Yangtze River; which, generally called the Jiangnan Spring Rains, has smaller precipitation intensity than the main monsoon rains (Tian and Yasunari 1998; Wan and Wu 2007, 2008). In South China, the onset of the rainy season is marked by the pre-flood season from mid-May to early June (Qin et al. 1994). The Mei-yu in the Yangtze River Basin begins from mid-June to early July (Chen 1983; Hu et al. 2008). In north and north-east China, the rainy season is delayed until mid-July to mid-August (Zhao 1994; Wang et al. 2006; Zhang et al. 2010) when the second flood season begins in South China (Ding and Wang 2008).

In late August, the rainy belt quickly withdraws southward. At this time, the autumn rains begin in the Wei River (a branch of the Yellow River) Basin, the Han River (a branch of the Yangtze River) Basin, eastern Sichuan, and other parts of central-west China. These rains are characterized by frontal precipitation with less severe rainfall (Xu and Lin 1994; Bai and Dong 2004). The rainy season extends over 1–2 months in most regions of the country, and contributes to approximately 30 %–60 % of the annual total rainfall. In eastern China, the rainy season undergoes latitudinal fluctuations driven by the summer monsoon. Clearly, China's rainy season is marked by regional differences and phase characteristics (Ding and Wang 2008). The rainy season in most parts of Japan begins around the time of China's Mei-yu, but arrives about 10 to 20 days later on the Korean Peninsula (Wang et al. 2007; Lau et al. 1988; Japanese Meteorological Agency 2004).

Previous research has focused on the seasonal characteristics of rainfall while paying less attention to the inter-decadal variations and the long-term trends of the indicators of the rainy season (Qian et al. 2002; Ding et al. 2008). Within the temperate zone of East Asia, the total and extreme precipitations in East China mostly increase in winter and decrease in autumn for the period 1961–2007 (Wang and Yan 2009). Korea's summer precipitation has significantly increased in recent years (Choi et al. 2008; Choi et al. 2009), whereas, in the Russian Far East and the northern part of North Korea, the summer precipitation has declined over the past 30 years (Yao et al. 2008). The inter-decadal variations of some aspects of the rainy season in some region are detected in several papers. The slower onset of East Asian summer monsoon has made the East China summer precipitation to decrease after the late 1970s, except for the Yangtze River basin (Jiang et al. 2008). At the same time, Korean summer monsoon rainfall peak has delayed (Lee et al. 2010), but the second peak advanced (Ho et al. 2003). The early rainy season precipitation significantly decreased in Eastern and Western Japan for period 1901–2009 (Endo 2011) and the onset of Baiu front delayed from 1959–1969 to 1986–1995 (Sato and Takahashi 2001) while the withdrawal of Baiu also delayed for period 1980–2000 (Inoue and Matsumoto 2003). However, a systematic analysis of the long-term variation of the rainy season for the whole region has been lacked.

The present paper analyzes the climatological characteristics and long-term variations of the rainy season in East Asia, using daily precipitation data from 1951 to 2009. Although the features of the rainy season in temperate East Asia are approximately similar to those of previous studies, the present study reports some new findings, especially for those from analysis of the long-term variations.

2. Data and method

2.1 Data and region

In this paper, the temperate zone of East Asia is defined as an area covering longitudes 105–145°E and latitudes 25–55°N (Fig. 1). This rectangular region includes the eastern part of China (excluding South China and Taiwan), the Korean Peninsula, Japan, central and eastern Mongolia, southern Siberia, and the Russian Far East. The region is of temperate and sub-tropical climate, but tropical regions, such as the South China and Taiwan are excluded from analysis.

The data used in this study are daily precipitation records from 1951 to 2009 and archived at the National Meteorological Information Center of China Meteorological Administration (CMA) and the Global Historical Climatology Network Daily (GHCN-D)

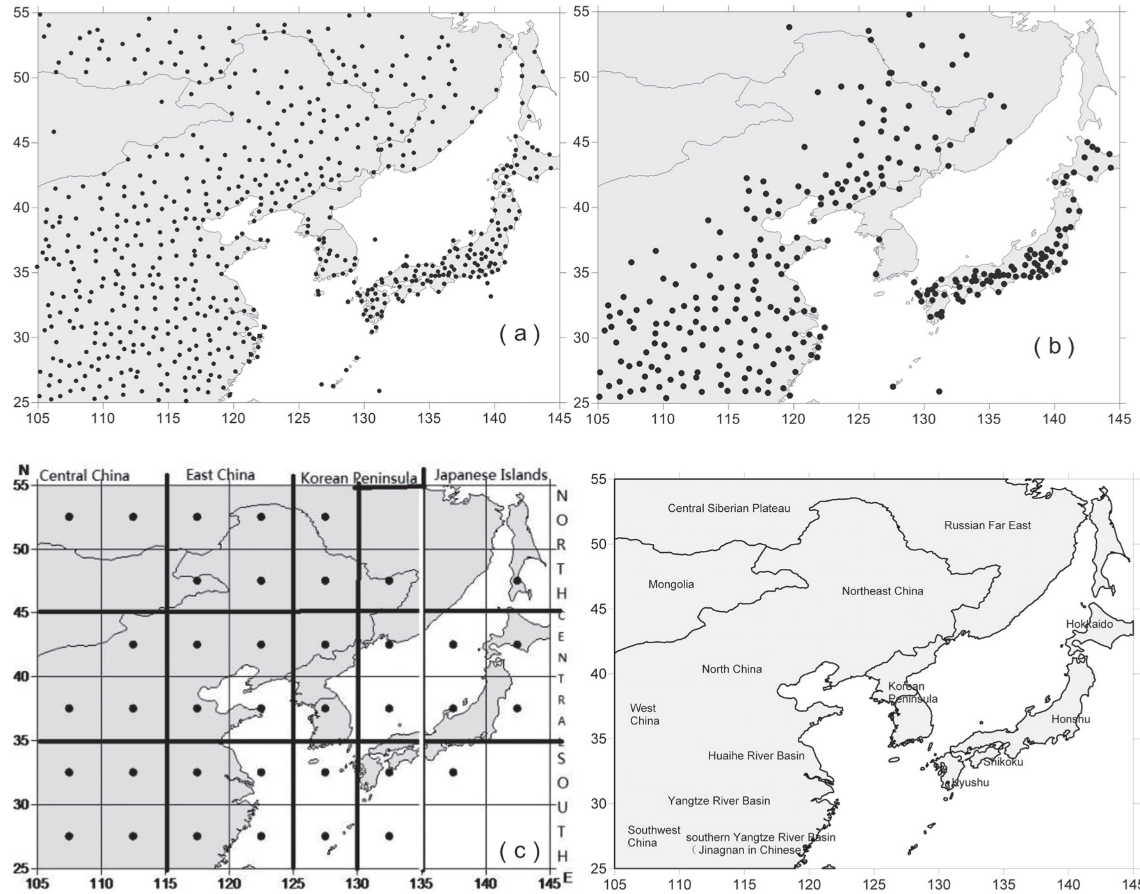

Fig. 1. (a) Distribution of precipitation stations in East Asia; (b) distribution of stations used to calculate the linear trend of single sites for analysis of spatial characteristics of trends; (c) grids with complete time series of daily precipitation data after interpolation for period 1951–2009, and thick lines divide the whole area into different longitude or latitude domains; (d) major geographical regions and their approximate positions as mentioned in the text.

dataset from US National Climate Data Center (NCDC) (Menne et al. 2012). Since the data quality and amount of missing data varies among stations, quality control was performed involving an extreme value check, exclusion of erroroneous data, examination of continuous constant values, and processing of missing records (Zhan et al. 2013). It was determined that the 1951–2009 period had to contain at least 33 years without missing data, and the reference period of 1971–2000 had to contain at least 20 years without missing data. Among the 619 stations selected for analysis, 343 stations are located in China, 145 in Japan, 20 in Korea, 6 in North Korea, 2 in Mongolia, and 103 in Russia. The spatial distribution of these stations is shown in Fig. 1a. The stations are uniformly and densely distributed throughout this region, with the density being the highest in Japan and lowest in Mongolia. Only two Mongolian stations were selected for use in the study due to the poor quality for Mongolian stations in the GHCND dataset.

2.2 *Definition of a rainy season*

This paper considers the pentad precipitation (total rainfall in a pentad), which is widely used in research of a rainy season. Each month is divided into six pentads of 5 days each, and a sixth pentad extending from Day 26 to the end of the month. Thus, a year is divided into 72 pentads. The pentad precipitation is accumulated by the daily precipitation. The start time, end time, and duration of the rainy season are all expressed in pentad units, where a pentad unit is the ordinal number of pentads of the start and end time of a rainy season. Similarly, the linear trend is expressed in units of day decade^{-1}.

There are several previous definitions of rainy season. If the research area is small, the rainy season can be defined based on an integrated index, which includes several stations in the area (Zhao 1994). Over a larger research area, the start and end dates of the rainy season are generally identified from the relative and absolute precipitation recorded by all stations during a pentad (Ding and Wang 2008). The relative precipitation method determines the entry of a rainy season by computing the ratio between the precipitation over one pentad to the climatologically mean pentad precipitation (Matsumoto 1997). The absolute precipitation method stipulates the rainy season standard as a pentad precipitation exceeding some specific threshold value (Lau and Yang 1997). In this paper, the study area is large enough, and a standard for each station is determined from the station's own observations of daily precipitation. Comparing the relative and absolute standards, the absolute precipitation method is found to be good in reflecting the actual climatology characteristics of the rainy season, while the relative rainfall method appropriately reflects the discrete degree of regional precipitation in a year but is a poor indicator of the real local precipitation (Matsumoto 1997). For example, in parts of southern China and along the coastal zones of Japan (especially at the Japan Sea side of Honshu and Hokkaido Islands, where precipitation is abundant throughout the year), the rainy season is not detectable by applying the relative precipitation method. Thus, we determine the rainy season by the absolute precipitation method.

The rainy season standard has been defined as an average daily precipitation of 6.0 mm (Lau and Yang 1997; Qian et al. 2002) or 5.0 mm for the daily precipitation minus the monthly averaged rainfalls in January (Wang and LinHo 2002). These standards are quite fitted in South Asia, Southeast Asia, and the lower latitude in East Asia, but a little stringent for areas up to 55°N, where the relatively heavy precipitation can be hardly formed due to the low temperature and scarce moisture in atmosphere. Therefore, we define the start and end dates of the rainy season as the first and last days of the pentads, respectively, on which the average daily precipitation exceeds 4.0 mm. The time between the start and end dates is the duration or length of the rainy season. In some parts of the study area, however, there are relatively dry seasons between the start and end dates of the rainy season (Inoue and Matsumoto 2003; Maejima 1967). In this paper, the relatively dry stages are called "the discontinuity of rainy season", which are the pentads with average daily precipitation less than 4.0 mm between the start and end dates. Because there is no Mediterranean climate (rainy winter and dry summer) in the study region, we have neglected any discontinuity of the rainy season in the rainy summer in this study. The discontinuities are included in the durations of the rainy season because they have not lasted for a long time (see Fig. 2b). Therefore, the duration of the rainy season can be regarded as the relatively rainy period of a year between the onset date of the rainy season and withdrawal date of the rainy season. According to the above standard, some stations record no rainy season (no pentad with average daily precipitation above 4.0 mm) and some can be classified as a type having rain for the entire year (more than 60 pentads with average daily precipitation above 4.0 mm). All other stations are divided into spring rain type, summer rain type and autumn rain type depending on the maximum number of pentads experiencing average daily precipitation above 4.0 mm within a year. Spring is from March to May, summer is from June to August, and autumn is from September to November.

Because of the large precipitation contingency, heavy rain can largely influence the analysis results of long-term change of the rainy season, causing large randomness. For a given standard, heavy rainfalls will significantly advance the start time and retard the end time relative to the climatology record. In this case, the long-term changes in the rainy season should be investigated under a stricter standard. If the average daily precipitation in two consecutive pentads exceeds 4.0 mm for the first time in a given year, the first pentad in the two consecutive pentads is regarded the start time of the rainy season. Similarly, if the average daily precipitation in two consecutive pentads exceeds 4.0 mm but falls below 4.0 mm in the next pentad and never simultaneously exceeds 4.0 mm in two consecutive pentads this year, the second of the two consecutive pentads marks the end time of the rainy season. The number of pentads between the start and end dates defines the duration or length of the rainy season. If no pentad in a year meets the standard or if no data are available during a year, they are not taken into account for the trend analysis.

2.3 Trend analysis

To analyze the changing characteristics of the rainy season, the linear trend from 1951 to 2009 was determined by two methods. The first method stip-

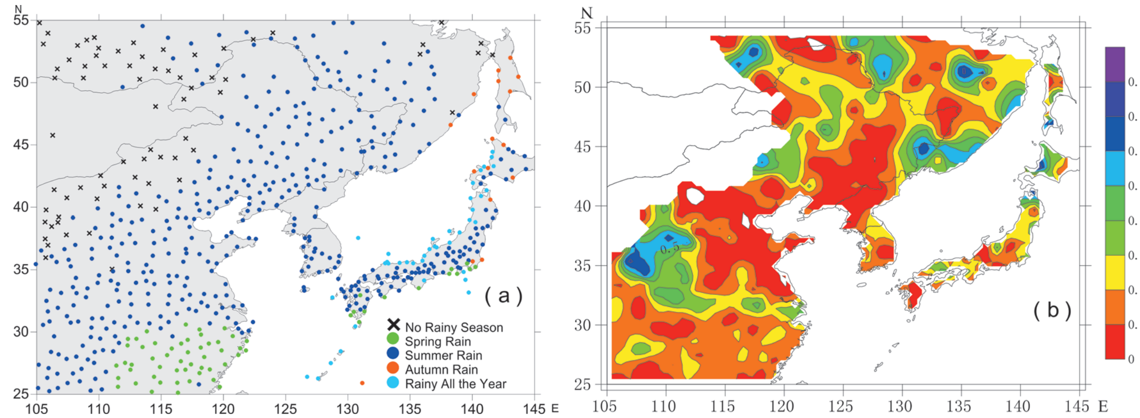

Fig. 2. (a) The types of rainy season of all the stations in East Asia; (b) the ratio of discontinuities to the whole rainy season.

ulates that every station has recorded a rainy season for at least 45 years throughout the past 59 years (75 % years of the research period), and stations with more than 14 years without a rainy season or without precipitation data are excluded. For selected stations, the few missing rainfall records are assumed as the averages of the 1951–2009 data. In this way, 345 stations are selected for analysis of spatial distribution of the long-term trends (Fig. 1b). The excluded stations are mainly located in rain-less areas such as Siberia, Mongolia, and Inner Mongolia. In these areas, rainy seasons are too scarce to admit a meaningful climate change analysis. However, most of the stations on the Korean Peninsula are also excluded because the data series in GHCND dataset are too short to have sufficient records for the trend analysis.

The second method establishes the regional average series by the grid area-weighted average method, adopted by Jones et al. (1999). The study area is divided into grids of 5° longitude by 5° latitude (Fig. 1c). The time series of pentad precipitation is obtained by arithmetically averaging the precipitation in each grid. Based on the mentioned standard above, the start, end time, and duration of the rainy season are determined in every grid. Where data are missing in a grid or where no rainy season has been recorded, the grid is considered to have no data for that year. These missing years introduce gaps in the time series of some grids. However, most of these grids have few missing data, and the gaps are filled by the following interpolation: if there are less than 5 missing years (or complete for at least 55 years), the missing years are interpolated by the mean rain data recorded in the grid throughout the study period. Or if there are more than 4 missing years, the grid is regarded as an empty grid, not participating in the regional average calculation. The interpolated grids are indicated by black solid circles in Fig. 1c. Empty grids are concentrated in Mongolia and the Russian Far East.

To compare the characteristics of the rainy seasons in different areas, the study area was divided into three parts by latitudes 35°N and 45°N. The northern part extends from 45 to 55°N, the middle part from 35 to 45°N, and the southern part from 25 to 35°N, as shown in Fig. 1c. The climatic condition of these regions roughly corresponds to the cool temperate zone, warm temperate zone, and sub-tropical zone, respectively (Pan et al. 1994). The regional average time series were calculated and compared among the three regions. Then, the linear trends of these time series were calculated and significant differences identified by the *t* test.

3. Results

3.1 Characteristics of the rainy season

Figure 2a shows the distribution of different categories of the rainy season in East Asia. Some areas, such as Middle Siberia, Mongolia, and Inner Mongolia, never meet the rainy season standard in any pentad due to the extremely low precipitation throughout the year. Therefore, most stations in southern Russia, Mongolia and Inner Mongolia have no rainy season. On the contrary the western coastal zones of the Japanese Islands are rainy all the year. The type of “Rain All the Year” in Fig. 2a is defined as those stations with the length of rainy season exceeding 60 pentads. Spring rain type occurs in southern Yangtze River and the southernmost coastal area of Japan. Autumn rain

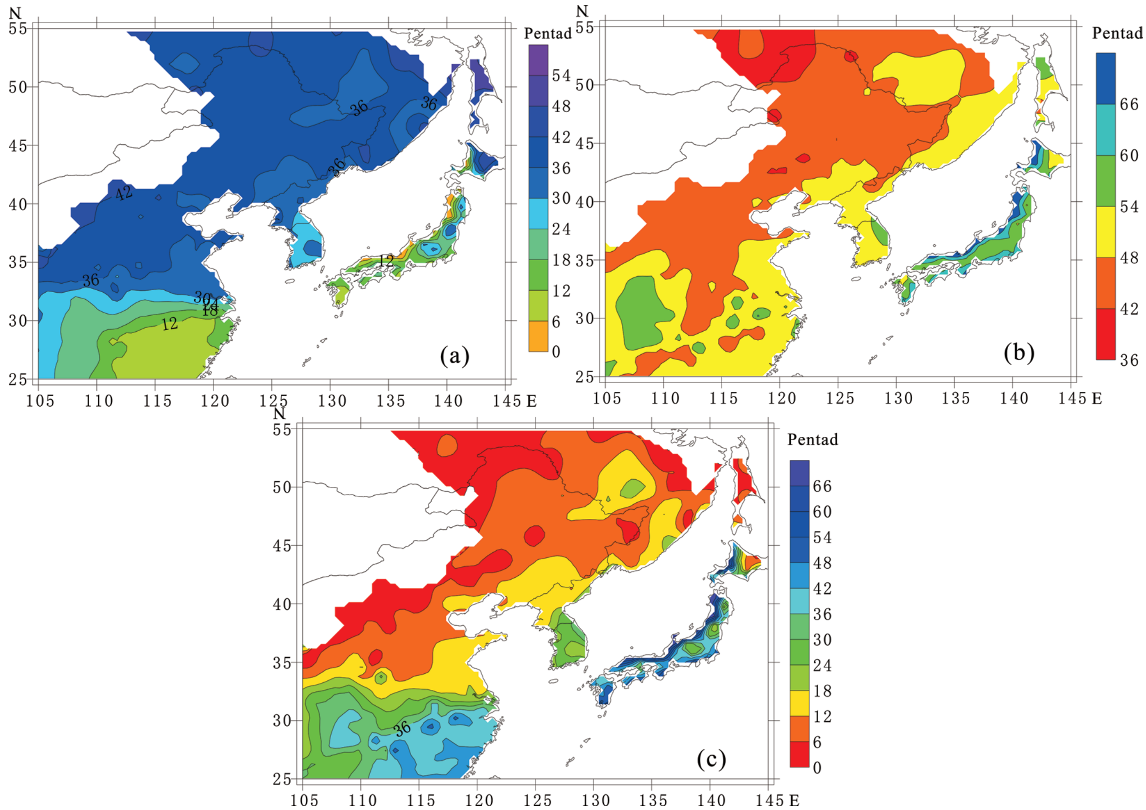

Fig. 3. Spatial distribution of the (a) start dates, (b) end dates and (c) length of rainy season in East Asia. Kriging interpolation is used in drawing the contours, and the contour intervals are 6 pentads for all the maps.

type only occurs in the Russian Far East (including Sakhalin Island) and some stations in the north of Japan. Other regions are all of summer rain type, indicating that precipitation mainly occurs during summer in most regions, dominantly in the temperate zone of East Asia.

In some parts of East Asia, the annual cycle of the precipitation is characterized by more than one peak, indicating that there may be more than one rainy seasons if other criteria for a rainy season are applied. The discontinuities exist between the start and end dates of the rainy season defined in this study. For example, there are two or three wet periods and relatively dry periods in between during the rainy season in some parts of Japan (Maejima 1967; Inoue and Matsumoto 2003). The discontinuities of the rainy season are less than 20 % of the entire rainy season in most areas, and between 20 % and 50 % in the Yangtze River basin, most mountainous regions in Russia and Northeast China and the north and west parts of the Honshu Island. Only in West China, a few of isolated sites in the Russian Far East and the western part of Hokkaido Island do the intermittent periods account for more than 50 % of the rainy season (Fig. 2b). These areas all have abundant autumn rain after their summer rainy season and the discontinuities between the summer rain and autumn rain. It is, therefore, reasonable to assume that the application of one rainy season a year is not causing an obvious bias.

Figure 3 displays the spatial distribution of the start and end dates and length of the rainy season in East Asia for the periods 1951–2009. The result is similar to the previous researches by Wang and LinHo (2002). However, there are some differences due to the usage of updated data, the lower standard applied for the rainy season and the neglect of discontinuities of the rainy season in this paper.

The onset of the rainy season propagates northwestward from the islands to inland, and this pattern is very similar to the previous researches for North China, Northeast China and Russia, but the onset

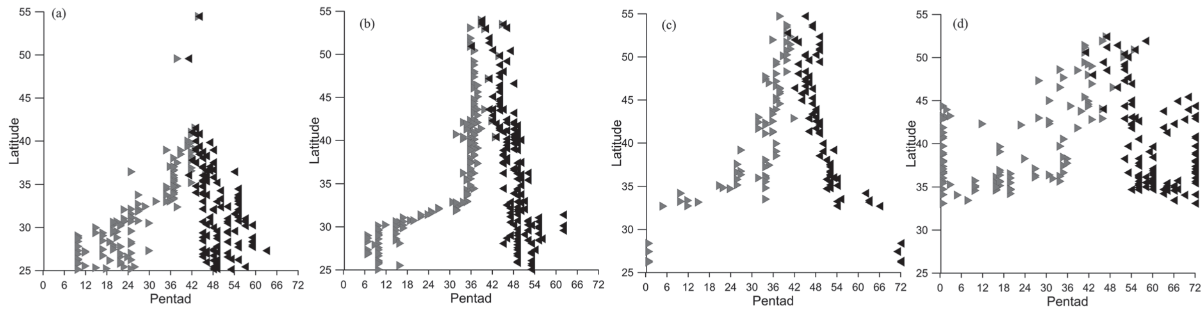

Fig. 4. The latitude–pentad profile of the rainy season in four longitudinal regions: (a) central China, (b) eastern China, (c) Korean Peninsula, and (d) Japanese Islands. Filled triangles denote the withdrawal dates and open triangles denote the onset dates.

starts apparently earlier in Chinese regions south of the Yangtze River, the Korean Peninsula, and most part of Japan than previous researches, as discussed in details below. The start dates of the rainy season differ markedly between the northern and southern parts in the Yangtze River Basin (30–33°N). From south to north, the start time of the rainy season changes from February–March to May–June, indicating that the rainy belt in this area slowly moves northward in spring. Thereafter, the rains rapidly develop in the Huaihe River Basin in China, northern part of the Korean Peninsula, and northeastern parts of the Honshu Island. The Russian Far East, northeast parts of Hokkaido Island as well as North and Northeast China, enter the rainy season in July or later.

The withdrawal pattern of the rainy season is not quite similar to the previous researches even in northern parts of the study region. The rainy season firstly withdraws in most parts of North China and Northeast China in August. The withdrawal of the rainy season in eastern China happens from north to south rather than from south to north as reported by Wang and LinHo (2002), and the end dates of the rainy season are much later than those of Baiu over western and central Japan (Sato and Takahashi 2001; Endo 2011). This is because most of the previous studies chose August as the end of the rainy season, but the autumn rain can still meet the standard of the rainy season defined in this paper, which lasts until September in the Yangtze–Huai River basin and the Korean Peninsula, and October in West China and most part of Japan. After October, the rainy season has ended in the entire East Asia except for the western coasts of the Japanese Islands. Overall, the southward retreat of the rainy belt in autumn is significantly faster than the northward advance in spring, and it does not linger for a long period in any areas.

The spatial distribution pattern of the rainy season duration is somehow different from the previous studies because all rainy stages are considered as a whole rainy season and the short discontinuities are neglected in this paper. The duration of the rainy season is longer in the southern areas than in the northern areas, and the longest rainy season in East Asia occurs in the northwestern coastal zones of Japan (Fig. 3c).

Figure 4 shows the start and end times of the rainy season as functions of latitude over four longitudinal zones (see Fig. 1c) in East Asia (inland or central China, 105 to 115°E; coastal or east China, 115 to 125°E; the Korean Peninsula, 125 to 130°E; and the Japanese Islands, 130 to 145°E). As the latitude increases, the rainy season begins later and ends earlier and the duration becomes shorter. During springtime, the rainy belt moves slowly northward and lingers in the subtropical regions for several months (from March to the first half of June). During summer (after mid-June), it rapidly shifts to the temperate regions north of 35°N. Late June is an obvious inflection time between the slow and rapid northward progress of the rainy belt. The inflection belt locates on the mainland at approximately 33°N (Fig. 4a, b) and on the islands at approximately 36°N (Figs. 4c, d). The rainy belt begins its rapid southward withdrawal in late August; by early October the sites with rainy season are restricted to the Japanese Islands.

The contrast between the four panels of Fig. 4 also reflects that, for given latitude (e.g., 30–40°N), the rainy season starts earlier, ends later, and lasts longer near the seas than that in inland areas. In particular,

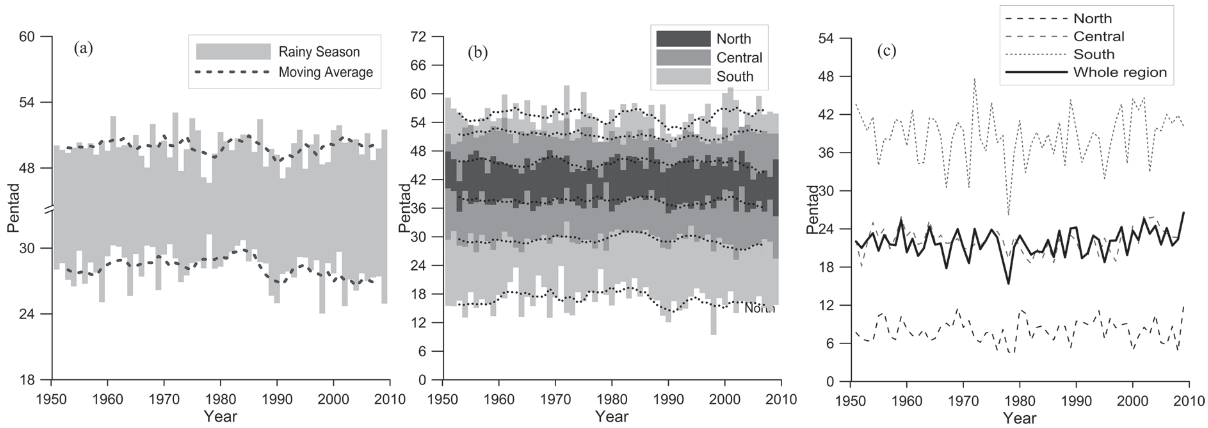

Fig. 5. Variation in regional averaged annual start dates and end dates of the rainy season in (a) East Asia and (b) the sub-regions, and (c) length (pentads) of the rainy season in all regions, dashed curves are the 5-year moving averages.

some stations in the Japanese Islands record much longer durations than other stations at the same latitude, illustrating that the marine regulating effect facilitates precipitation in autumn and winter. The relatively abundant autumn and winter precipitation mainly results from the northwestern winter monsoon over the Sea of Japan and the movement of extra-tropical cyclones. The cold northwesterly flow over the warm surface of the Sea of Japan in autumn and winter leads to frequent and large precipitation on the western coast of the Japanese Islands. The phenomenon can be called as “sea-effect precipitation” (Estoque and Ninomiya 1976). The similar cold-season precipitation also appears in the southeastern coastal zone of the Great Lakes, southern coastal areas of the Caspian Sea and northernmost part of Taiwan (e.g., Miner and Fritsch 1997; Laird et al. 2009).

From 30 to 35°N of eastern China, the Korean Peninsula and some part of the Japanese Islands, the rainy season begins in February, March or April in the south, to late June in the north, indicating a slow northward movement of the rainy belt. This is consistent with those reported in previous studies (e.g., Ding 1994; Tanaka 1992), but the most rapid propagation of the onset time occurs around 36th pentad in eastern China, followed by that in the Korean Peninsula, indicating that the accelerated northward movement of rainy belt in late June to early July in East Asia.

3.2 Long-term changes the in rainy season

Figure 5a plots the averaged start and end dates of the rainy season in East Asia. The regional average annual dates of entering the rainy season range between the 21st–30th pentads, corresponding to mid-April to late May, and the rainy season generally ends between pentads 48–56, i.e., from the end of August to early October. The time period between these dates, or the length of the rainy season, is mostly between 90 and 170 days.

The start and end dates of the rainy season advanced by approximately 0.91 day decade^{-1} and 0.43 day decade^{-1} respectively (about 5.5 and 2.5 days, respectively, throughout the whole period). However, these changes were insignificant at the 0.05 significance level (Table 1). The start time of the rainy season was delayed from the 1950s to the 1980s but suddenly advanced in the 1990s and 2000s. The rainy season ended earliest in the 1990s and latest in the 2000s (Table 1). The moving 5-year average (Fig. 5a) reveals similar decadal fluctuations in the start and end times of the rainy season, up to the 1990s.

Figure 5b displays the regional area-weighted average start and end dates of the rainy season in the northern, central, and southern areas of temperate East Asia. The gray area in the figure represents the length of the rainy season. The rainy season arrived first in the southern part of East Asia, in March or April, and reached the central part in late May to early June. In most years, it finally reached the northern part in July. Conversely, the rainy season terminated earliest in the northern part (in August of each year), later

Table 1. Regional average start dates, end dates, and duration anomaly for each decades (unit: pentad) and their linear trends for the whole period, of the rainy season in various parts of East Asia during 1951–2009 (unit: day decade^{-1}). All trends are not statistically significant at the 0.05 significance level.

	East Asia			North			Central			South		
	Start	End	Duration	Start	End	Duration	Start	End	Duration	Start	End	Duration
1950s	−0.8	0.5	1.3	0.4	0.5	0.0	−0.8	0.6	1.4	−1.5	0.4	1.9
1960s	0.0	0.7	0.6	−0.3	−0.1	0.2	−0.6	0.9	1.5	0.8	0.9	0.0
1970s	0.3	0.1	−0.2	0.6	−0.5	−1.1	−0.4	0.3	0.6	0.8	0.4	−0.5
1980s	0.7	0.5	−0.1	0.2	0.5	0.3	0.8	0.2	−0.6	0.8	1.0	0.2
1990s	−0.9	−0.9	0.0	−1.0	0.2	1.2	−0.3	−0.6	−0.3	−1.5	−1.7	−0.2
2000s	−1.3	0.9	2.3	−0.4	−0.8	−0.4	−2.1	1.0	3.1	−1.1	1.9	3.0
Linear trend [day (10 yr)$^{-1}$]	−0.91	−0.43	0.48	0.00	−0.98	−0.70	0.28	0.00	−0.81	−0.42	0.39	0.00

in the central region (September of each year), and latest in the southern part (in September or October). The end time of the rainy season was considerably more similar among the areas than the start time. In individual years, the rainy season ended earlier in the southern part than the central part, supporting that the southward retreat of the autumn rains is faster than the northward advance of the spring rains. This feature was especially noticeable at lower latitudes but exerted no significant effect throughout the study period, indicating that the speed of the rain belt movement was more or less constant throughout some decades. The start and end times of the rainy season temporally advanced in all regions of East Asia, but the trend was insignificant ($p > 0.05$; Fig. 5b and Table 1). These slight changes might be associated with the reduced autumn rain in this region (Wang and Yan 2009).

The characteristics of the area-weighted average length of the rainy season in East Asian areas are plotted in Fig. 5c. Throughout East Asia, a typical rainy season lasted 18–30 pentads (namely 3–5 months). The rainy season lengths are the longest in the southern parts of East Asia (5–6 months), medium in the central parts (3–4 months), and the shortest in the north (about 1 month). Because the start time more rapidly advanced over the decades than the end time regardless of region, the duration of the rainy season increased slightly in all regions, but the increases are all statistically insignificant ($p > 0.05$; Table 1). The duration increased by 0.48 day decade^{-1} throughout the whole East Asia, equivalent to a 3-day increase over the study period, but again, this trend was insignificant. Although the duration fluctuated in each area of East Asia, it remained longest in the southern parts, intermediate in the central parts, and shortest in the northern parts. The duration of the rainy season decreased from the 1950s to 1970s and increased after the 1970s (Table 1).

An interesting phenomenon is that the annual start and end dates of the rainy season in East Asia on the whole, or in each of the sub-regions, has an approximately consistent variation on the decadal scale, that the start dates generally simultaneously advancing or delayed together with the end dates (Figs. 5a, b). This harmonic variation seems more obvious before the mid-1990s, leading to a more or less depressed change in the rainy season length.

Figure 6a displays the spatial distribution of the trends of annual start dates of the rainy season. Areas without a rainy season such as Russia's Siberia, Mongolia, and China's Inner Mongolia lack sufficient data for conducting a trend analysis of the rainy season; the western coast of the Japanese Islands are also excluded because they rain throughout the year. Stations in China and southern coasts of Japan recorded the largest temporal advance of the start time, and the advance at some stations in the Yangtze River Basin passed the 0.05 significance test. Stations in the Korean Peninsula and Hokkaido exhibited an increasingly delayed start time, but the trends were not significant.

Figure 6b shows the spatial distribution of the trends of annual end dates of the rainy season. The end time was increasingly advanced in the Russian Far East, North and Northeast China, the southwestern part of China and the southeastern coast of Honshu Island, but the trends were only significant at a few stations in China. Areas in southeastern China, the eastern coasts of Japan's Hokkaido and Kyushu Islands, and inland of Honshu Island experienced an increasingly delayed end time throughout the study period.

Figure 6c displays the temporal changes in the

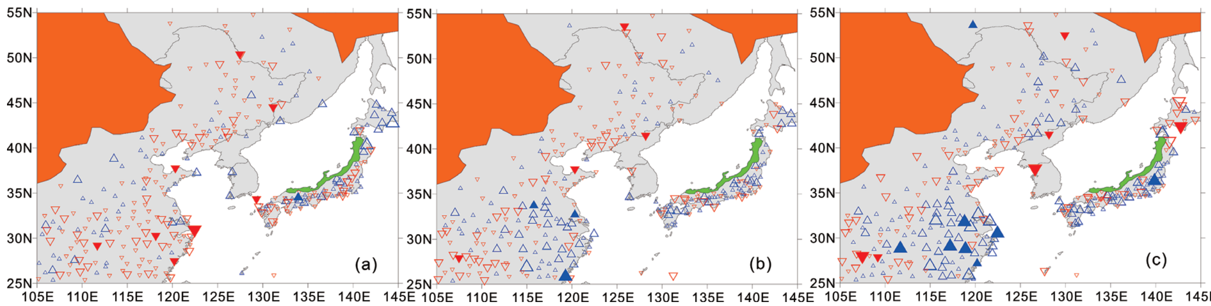

Fig. 6. Spatial distribution of the trends of annual (a) start dates, (b) end dates, and (c) lengths of the rainy season in East Asia during 1951–2009 (Negative values mean advance for (a) and (b) or decrease for (c), and positive values mean delay for (a) and (b) or increase for (c). Filled triangles mean that the trends are statistically significant at the 95 % confidence level and open triangles are statistically insignificant at the 95 % confidence level. Orange areas indicate no rainy season and green ones indicate rainy season throughout the year.

duration of the rainy season. Throughout the study period, the rainy season became shorter in the Russian Far East, northern and western China, the Korean Peninsula, and the Hokkaido Island in Japan. Significant reduction was observed in parts of southwestern China, the western coasts of the Korean Peninsula, and the southern Hokkaido Islands. Conversely, it was significantly increased in the Yangtze River and the Huaihe River Basins in China (where the rate exceeded 1.5 pentads per decade; $p < 0.05$).

4. Discussion

In this study, we analyze climatological characteristics and temporal variation of the start and end dates of the rainy season over East Asia. Our analysis of climatological characteristics draws some conclusions similar to those of previous studies, but certain results reported here are different from the previous works. The differences in previous studies mainly derive from the methods used to define rainy season, including the different treatments of discontinuities within the rainy season which are neglected in our analysis while other analyses generally accounting for them in varied extents, and also from the different criteria of pentad average daily rainfall with this analysis applying a lower threshold. Previous researches, such as Wang and LinHo (2002), mostly neglected the shorter rainy stages with daily precipitation of about 4–6mm, but these stages are regarded as parts of the rainy season in this paper. Thus, rainy stages such as spring rain over southern Yangtze River basin and autumn rain over West China and western and central Japan were included in the rainy seasons in this paper. As a consequence, the climatological feature of the rainy season, especially the withdrawal pattern, exhibits certain differences from that of the previous studies. However, the precipitation in the shorter rainy stages usually plays a critical role in the agricultural production and is valuable to be considered in the rainy season research especially for the regions without so much precipitation in the growth season.

The long-term trends of the rainy season have also some similarities to and differences from those observed in the previous studies. The start and end dates of the rainy season have advanced over time in North and Northeast China, consistent with previous reports of increasing spring rain and decreasing autumn rain (Ren et al. 2000; Qian et al. 2002; Wang and Yan 2009). However, the present study found an advance of the start date and a retardation of the end date in the Yangtze–Huaihe River Basins, contradicting the decreased spring rain and increased summer rain in the river basin reported by Wang and Yan (2009). This discrepancy can be explained by the increased precipitation in most regions of China during winter months. Consequently, in February of the recent years, data collected from areas south of the Yangtze River Basin would have met the relatively less stringent rainy season standard of the present study. On the other hand, typhoons usually bring huge precipitation and the frequency of typhoons can substantially change the summer and autumn precipitation characteristics in East Asia, including modifying the withdrawal pattern of the rainy season in eastern China and southern Japan. Previous studies found that most typhoons moved to China instead of Japan after 1984 (Inoue and Matsumoto 2007). This might be a reason for the delayed withdrawal dates of the rainy season in Southeast China and the advanced withdrawal dates of the rainy season in the Pacific side of Honshu, as revealed in this paper. Although what Inoue and Matsumoto (2007) investigated is the recent changes of typhoon passage frequency during late August, the typhoon passage pattern might experience a similar temporal change in autumn after mid-1980 over the study region.

The parallel decadal variation of the start dates of the rainy season with the end dates before the mid-1990s is worth further investigation. It might have been related to the onset and close dates of the East Asian Summer Monsoon, implying that the close dates of the monsoon will be earlier (later) when the onset dates begin earlier (later). The correspondence might be of relevance for understanding and prediction of the close time of the summer monsoon and rainy season on East Asia. However, the simultaneous advance and delaying have become less obvious since the mid-1990s. The reason for the diversion has been not known, and it deserves further study. Kajikawa et al. (2012) reported that East Asia summer monsoon experienced an advanced onset date in May in recent decades. This might have been one of the reasons for the observed advance of the rainy season in the Yangtze River Basin in this paper. Kitoh and Uchiyama (2006) showed that the changing characteristics of the onset and withdrawal of the early summer rain will occur from southwest to northeast of East Asia for period 2081–2100 based on CMIP3 GCM output, which may reflect a possible response of the East Asian monsoon to the anthropogenic global climate change.

There are some deficiencies in the present research. For example, the discontinuities of the rainy season are all neglected in this paper, but some small parts of the study region have a wide variety of discontinuities. The duration of the rainy season there becomes much longer than traditionally believed; The lower threshold of the rainy season may fit better in high latitudes of China and Russia, but a little less in southern China and Japan, though this treatment is necessary for a large region like East Asia. It may be better to use different thresholds on the basis of the precipitation distribution in a year for studies of any smaller regions. In addition, the East Asian region is subjectively divided into three parts (northern, central, and southern), and this precludes a more detailed longitudinal analysis of the difference of the rainy season change between coastal and inland regions. All of these will be strengthened in the future studies.

5. Conclusions

Based on daily precipitation data, this study analyzed the climatology and long-term change characteristics of the rainy season over the past several decades in East Asian region. The main conclusions are summarized below.

(1) From the northwest inland regions to southeast coastal regions, a spatially dependent change in the start and end dates of the rainy season is observed; namely, the rainy season begins earlier, ends later, and lasts longer in coastal regions. Siberia, Mongolia, and China's Inner Mongolia are relatively dry regions with no rainy season. In contrast, the southeast part of China, Kyushu Island, and the western coast of Honshu and Hokkaido Islands remain wet throughout the year. Generally, the start date of the rainy season becomes increasingly delayed with latitude for every longitude zone. From 30 to 35°N, the setup of the rainy season has a difference of few months, indicating a slow northward movement of the rainy belt through this latitude belt.

(2) From 1951 to 2009, the regional average start and end dates of the rainy season gradually advanced throughout East Asia, increasing the duration of the rainy season, but none of these changes passed the significance test ($p > 0.05$). To varying but insignificant extent, the same trends were observed in the northern, central, and southern regions of East Asia.

(3) The rainy season seemed to begin earlier in China but later in Korea and Japan. Throughout the study period, the rainy season withdrew earlier at latitudes north of 35°N, and particularly advanced in southwest China, while the end date was delayed in the Yangtze–Huaihe River Basins.

(4) The length of the rainy season has slightly reduced in the Russian Far East and in northern and western China and significantly reduced on the Korean Peninsula and the southern Hokkaido Islands. An obvious increase in the rainy season length was observed in the Yangtze–Huaihe River Basins.

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