Long-Term Changes of Seasonal Progress in Baiu Rainfall Using 109 Years (1901−2009) Daily Station Data

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Abstract

This study investigates long-term changes in Baiu rainfall in Eastern and Western Japan using daily precipitation records at 37 stations for the years 1901 through 2009, focusing on its seasonal progress. This period is much longer than various data analyzed in previous observational studies. In the early Baiu season (early to mid June), significant long-term decreasing trends are observed in Eastern and Western Japan, accompanying large inter-decadal variation in the former half of the 20th century. In the late Baiu season (mid to late July), in contrast, significant long-term increasing trends are observed on the Japan Sea side of Eastern and Western Japan. No significant trends are recognized either in the mid Baiu season (late June to early July) or in the entire Baiu season (June to July) over all regions. It is interesting to note that the observed tendency of delayed Baiu withdrawal in the last 109 years, when global warming has been in progress, is similar to its future changes projected by climate models.

1. Introduction

The rainy season in early summer over East Asia, which is generally called the Baiu season in Japan, is brought by northward migration of a narrow rain band with a stationary frontal zone from May to July. In Japan, a clear climatological rainfall peak is observed in the Baiu season. By the end of July, the frontal zone reaches northern Japan and becomes unclear, while concurrently the midsummer season starts over many parts of Japan. The transition is characterized by an increase of sunshine duration and temperature and a decrease of precipitation (Ninomiya and Murakami 1987; Matsumoto 2002).

According to observational studies, the withdrawal of the Baiu season over Japan has been delayed and climate in the midsummer season following the Baiu season has been unstable in the latter half of the 20th century. Yamakawa (1988) investigated prevailing surface pressure patterns using the daily surface weather charts for the period 1941−1985 and found that the withdrawal of the Baiu season has become later after the late 1970s. Sato and Takahashi (2001) compared sunshine durations from 1 to 10 August between two periods of 1959−1968 and 1986−1995 over Japan and found that sunshine duration for the later period was significantly less compared with that for the earlier period. They concluded that the change is caused by the slower northward movement of the Baiu frontal zone than before. Inoue and Matsumoto (2003) investigated sunshine durations for the periods 1951−2000 over Japan and found that the withdrawal of the Baiu season has been delayed since the 1980s in central and western Japan. Inoue and Matsumoto (2006) compared the two periods of 1961−1979 and 1980−1999 regarding precipitation over East Asia, as well as sunshine duration and temperature over Japan. They found that northward movement of the Meiyu-Baiu frontal zone becomes slower in the later period and that midsummer (16 July to 15 August) with cool temperatures and little sunshine has frequently appeared in central Japan since the 1980s.

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The data analyzed in the previous observational studies were restricted within the latter half of the 20th century. This is of insufficient length in order to discuss whether these observed trends are forced by external influences such as anthropogenic activities because inter-decadal natural climate variability cannot be discounted in a 50-year-or-shorter record (Wang et al. 2007). In addition, the trends indicated by the previous studies are not necessarily tested statistically enough. Therefore, it is necessary to investigate long-term trends of the seasonal delay using much longer observed data and using statistical tests.

Historical daily precipitation data at all stations of the Japan Meteorological Agency (JMA) were recently digitalized, and JMA conducted a quality check of the data at 51 stations where the uniformity of observation data has been maintained since 1901 (Fujibe et al. 2006). Using this precipitation dataset, which has much longer temporal coverage than the various data analyzed in previous studies, we studied long-term changes of the Baiu rainfall during the last 109 years in Japan, focusing on its seasonal progress. Stations in the Tohoku region (northernmost part of the main island of Japan), where the Baiu season exists, are not included in this study because the Baiu season over this region is marked by a minimum sunshine duration, not by a rainfall peak (Ninomiya and Murakami 1987).

2. Data

The daily precipitation data at 37 selected JMA stations, which are in Eastern Japan and Western Japan, were analyzed for the period 1901 to 2009. The stations were divided into four regions of the Japan Sea side of Eastern Japan (EJ), the Pacific side of Eastern Japan (EP), the Japan Sea side of Western Japan (WJ) and the Pacific side of Western Japan (WP), as shown in Fig. 1. See the details of the divisions in JMA (2005a). We also defined combined regions of the Japan Sea side of Eastern and Western Japan (EJ+WJ), the Pacific side of Eastern and Western Japan (EP+WP) and Eastern and Western Japan (E+W). The total number of stations included in these regions is 3, 15, 8, 11, 11, 26 and 37 for EJ, EP, WJ, WP, EJ+WJ, EP+WP and E+W, respectively. Details of

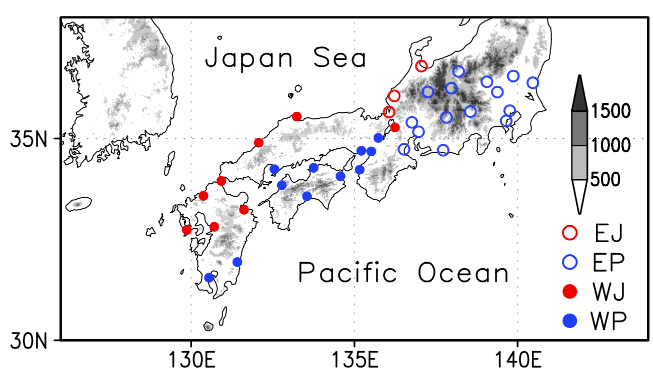

Fig. 1. Location of stations analyzed in this study. Regional divisions are: Japan Sea side of Eastern Japan (EJ) (red circle), Pacific side of Eastern Japan (EP) (blue circle), Japan Sea side of Western Japan (WJ) (red dot), and Pacific side of Western Japan (WP) (blue dot). Shade indicates topography (unit: m).

the stations analyzed are listed in supplement Table S1.

In preprocessing, historical daily data is averaged for 10-day or 11-day periods at each station (e.g., 1 to 10 (early) July, 11 to 20 (mid) July and 21 to 31 (late) July in 2002). The averaged data was calculated only when more than 80% of daily data had normal or quasi-normal flags (JMA 2005b) in each 10-day or 11-day period. There are hardly any missing records in the dataset, as also shown in Table 1 in Fujibe et al. (2006). For regional averages, normalized data at each station (i.e., the ratio relative to the averages over the base period (1901−1930)) are used in order to average with the same weight on each station data, except for Fig. 2.

3. Results

Figure 2 shows 10-day mean precipitation from late May to mid August in the first 30 years (1901−1930) and in the last 30 years (1980−2009) of the analyzed period. Much rainfall is observed in the period from June to July over all regions, especially over Western Japan (WJ and WP). The rainy period in Western Japan slightly precedes that in Eastern Japan (EP and WP) because the rainy season is brought by the northward migration of a rain band over East Asia (Ninomiya and Murakami 1987). Rainfall peaks are observed in late June for EP, WJ and WP and in early July for EJ in the first period.

We can see changes in the climatological rainfall from the first period to the last period. In many regions, precipitation decreases in early to mid June, while precipitation increases in mid to late July. It seems that the rainy season somewhat shifts later from the first period to the last period, especially over EJ and WJ. The time for rainfall peaks did not change except for EJ, where the peak timing shifted to mid July.

Figure 3 shows regional mean long-term trends from 1901 to 2009 by 10-day intervals. The trends are derived by applying the linear regression to the regional averages of the normalized precipitation at each station. Precipitation has decreasing trends for early to mid June (i.e., before the Baiu rainfall peak) in many regions. Decreasing trends at a rate of approximately 25% per century are observed in all regions in mid June. On the other hand, precipitation has increasing trends for mid to late July (i.e., after the Baiu rainfall peak) in many regions. Remarkable increasing trends at a rate of over 50% per century are observed in WJ in mid to late July and in EJ in mid July. It is also noted that precipitation decreases in early August in all regions.

Long-term trends indicate different features depending on the stage of the Baiu season and on the region (Fig. 2 and Fig. 3). Next, we analyze long-term trends and variations in four periods related to the stage, consisting of the early Baiu season (Period 1: 1 to 20 June), the mid Baiu season (Period 2: 21 June to 10 July), the late Baiu season (Period 3: 11 to 31 July) and the entire Baiu season (Period 4: 1 June to 31 July). To estimate the robustness of the long-term trend, two types of statistical significance tests are applied. One is based on the linear regression model using the least-square (LS) method and the other is based on the nonparametric Mann-Kendall (MK) rank statistic (Kendall 1938).

Table 1 shows long-term linear trends of precipitation for 1901−2009 in each region and in each period and their statistical confidence levels using the MK method and the LS method. In Period 1, decreasing trends are found in all regions with ranges from −17% (WP) to −23% (WJ). The trend in E+W (−20%) is significant at the 90% confidence level in both tests, although the trends in other local regions do not reach the 90% level in either test. In Period 3, on the other hand, quite large increasing trends are found on the Japan Sea side (EJ (+54%), WJ (+54%) and EJ+WJ (+54%)) with significance at the 90% or 95% level, while increasing trends on the Pacific side (EP (+3%), WP (+8%) and EP+WP (+5%)) are small. In particular, confidence levels of the trends in EJ+WJ reach the 95% level in both tests. Interestingly, trends in Period 2 and Period 4 are not clear, although those in the regions on the Japan Sea side are relatively large but are not statistically significant. It should be noted again that statistically significant long-term trends are observed in the early and late stages of the Baiu season, but not in the middle stage of the Baiu

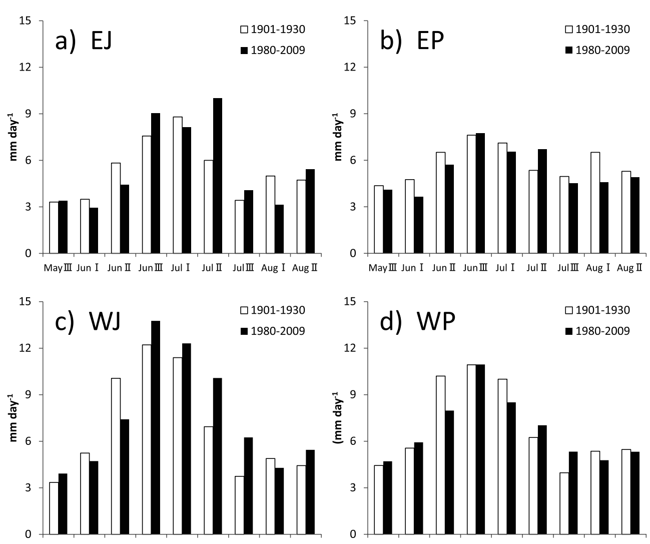

Fig. 2. Regionally averaged 10-day mean precipitation (mm day^{-1}) from late May to mid August in the first 30 years (1901−1930: white bars) and in the last 30 years (1980−2009: black bars). (a) EJ, (b) EP, (c) WJ, (d) WP. Key: I = 1 to 10, II = 11 to 20, III = 21 to 30 (or 31) days of each month.

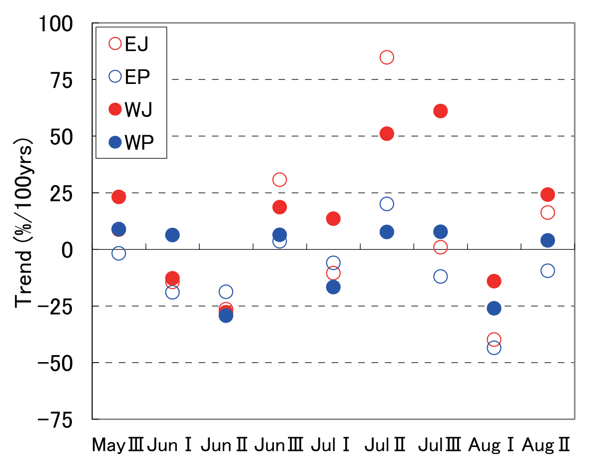

Fig. 3. Linear trends (% per 100 years) of regional mean precipitation ratios for 1901 through 2009.

Table 1. Linear trend (% per 100 years) of regional mean precipitation ratio for 1901 through 2009 and its confidence level determined using the Mann-Kendall (MK) method and the least-square (LS) method. One (two) asterisk denotes statistical significance at the 90% (95%) confidence level. Period 1: 1 to 20 June. Period 2: 21 June to 10 July. Period 3: 11 to 31 July. Period 4: 1 June to 31 July

Region	Period 1			Period 2			Period 3			Period 4		
	Trend	MK	LS	Trend	MK	LS	Trend	MK	LS	Trend	MK	LS
EJ	−22			8			54	*	*	13		
EP	−19			−2			3			−7		
WJ	−23			16			54	*	**	12		
WP	−17			−5			8			−6		
EJ+WJ	−23			14			54	**	**	12		
EP+WP	−18			−3			5			−6		
E+W	−20	*	*	2			20			−1		

nor the entire Baiu season.

Figure 4 shows the time series of regional mean precipitation ratio relative to the 1901−1930 average in Period 1, Period 2 and Period 3. In this figure, results of EJ+WJ and EP+WP are given because features in the long-term trends are similar between EJ and WJ and between EP and WP (Fig. 3 and Table 1). In Period 1 (Fig. 4a), precipitation has been decreasing with large year-to-year variations in EJ+WJ and EP+WP. The 11-year running mean precipitation in both combined regions fluctuates in a similar way. Precipitation has clearly decreasing trends in the latter half of the analyzed period, while precipitation exhibits large inter-decadal variability in the former half of the analyzed period. In Period 3 (Fig. 4c), precipitation has been increasing with large year-to-year variations in EJ+WJ. The 11-year running mean precipitation increases abruptly in EJ+WJ around the 1940s and a large difference from that in EP+WP is observed after the 1960s. It is also noted that heavy rainfall years (1957, 1971, 1972, 1982, 1983, 1987, 2003 and 2006) exceeding 250% are observed only in the latter half of the analyzed period in EJ+WJ. In other words, interannual variability of rainfall has been greatly increasing in the late Baiu season in EJ+WJ. Standard deviations of the variability in the region in the late Baiu season are 66%, 77%, and 96% for the period 1901−1940, 1941−1980 and 1981−2009, respectively. In Period 2 (Fig. 4b), long-term trends are not clear, as also shown in Table 1, but with relatively large decadal variability showing decreased rainfall around the 1940s and increased rainfall around the 1950s and the 1960s.

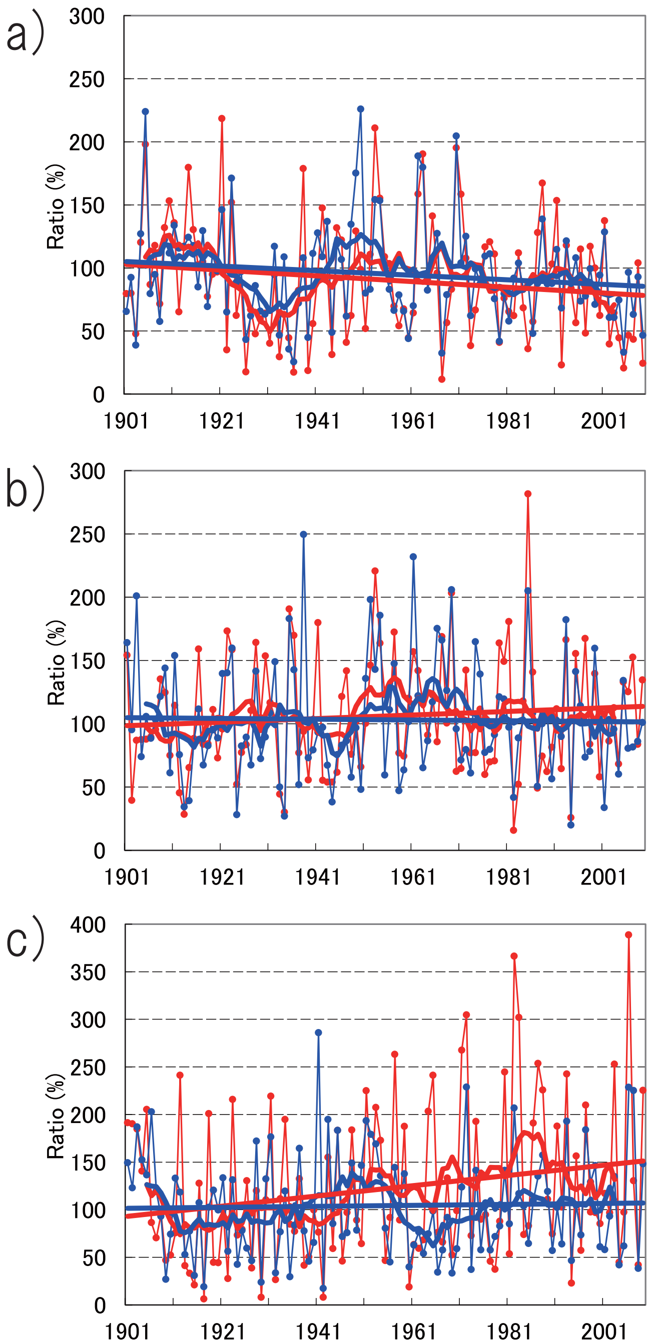

Fig. 4. Time series of regional mean precipitation ratios in (a) Period 1, (b) Period 2 and (c) Period 3. Red line: EJ+WJ. Blue line: EP+WP. The thick lines indicate the 11-year running mean. The straight lines are obtained by linear regression. The base period of the ratio is 1901 through 1930.

Figure 5 shows spatial distribution of the trends and its statistical significance based on the MK test. In Period 1 (Fig. 5a), decreasing trends are observed over almost all of the stations. Stations with significant decreasing trends are distributed over central Japan and the Japan Sea side of western Japan. Twelve stations have significant decreasing trends at the 90% level. In Period 3 (Fig. 5b), both decreasing and increasing trends are observed although stations with increasing trends are dominant. Stations with large increasing trends are mainly distributed on the Japan Sea side of Japan. Six stations have significant increasing trends at the 90% level. In Period 2 (not shown), no station has trends at the 90% level. In Period 4 (not shown), two stations (Sakai and Hamada) have increasing trends, while one station (Tsu) has a decreasing trend at the 90% level.

4. Summary and discussions

We investigated long-term changes in Baiu rainfall in Eastern and Western Japan using daily precipitation records at 37 stations for the period 1901 to 2009, focusing on its seasonal progress. In the early Baiu season (early to mid June), significant decreasing trends with a 90% confidence level are observed in Eastern and Western Japan, accompanying large inter-decadal variation in the former half of the 20th century. In the late Baiu season (mid to late July), in contrast, significant increasing trends with a 95% confidence level are observed on the Japan Sea side of Eastern and Western Japan, while clear trends are not found on the Pacific side. No significant trends are recognized either in the mid Baiu season (late June to early July) or in the entire Baiu season (June to July) over all regions. In addition, not only averaged rainfall but also interannual variability of rainfall has been increasing on the Japan Sea side in the late Baiu season.

This study reveals that precipitation has a long-term increasing trend with statistical significance on the Japan Sea side of Eastern and Western Japan in the late Baiu season. This trend of delayed Baiu withdrawal is consistent with that shown by previous studies analyzing observational data in the latter half of the 20th

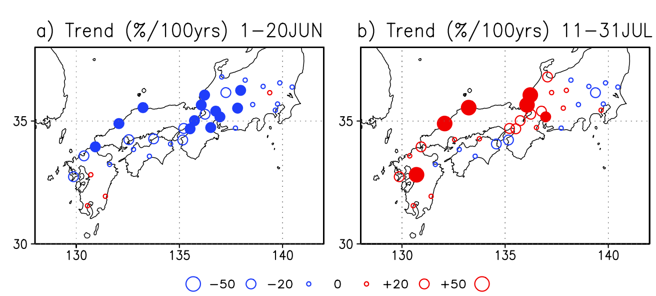

Fig. 5. Geographical distribution of linear trends of precipitation for 1901 through 2009 in (a) Period 1 and (b) Period 3. Red (blue) circles indicate increasing (decreasing) trend. The size of each mark reflects the magnitude of the trend. Filled circles denote statistical significance at the 90% confidence level by the MK test.

century (Yamakawa 1988; Sato and Takahashi 2001; Inoue and Matsumoto 2003; Inoue and Matsumoto 2006; Takahashi 2009). Observational stations with the long-term trend in the late Baiu season are mainly on the Japan Sea side. Why is the trend clearer at stations on the Japan Sea side? According to Yamakawa (1988), Sato and Takahashi (2001) and Inoue and Matsumoto (2006), the Baiu frontal zone is clearer and stays longer from the late Baiu season to the following midsummer season in recent decades. These trends would bring regions on the Japan Sea side more rainfall because the mean frontal zone is over the Japan Sea during the season. In addition, Nagata and Mikami (2010) reported, based on the HadSLP2 (Allan and Ansell 2006), that the North Pacific subtropical high has extended southwestward in the 20th century. It is likely that this long-term change alters moisture transport, which might affect the observed long-term rainfall trend.

Latest future projections with climate model studies indicate that global warming induced by increasing greenhouse gases will lead to increased Baiu rainfall and a delay of the Baiu withdrawal (Kimoto 2005; Kitoh and Uchiyama 2006; Kusunoki et al. 2006; Kusunoki and Mizuta 2008). It is interesting to note that the observed tendency of delayed Baiu withdrawal in the last 109 years, when global warming has been in progress, is similar to the projected future changes.

This study also reveals that precipitation has a long-term decreasing trend with statistical significance over Eastern and Western Japan in the early Baiu season. Inoue and Matsumoto (2003) showed a similar tendency based on observed sunshine duration data for the period 1951−2000, although the trend was not so clear in their results. This observed trend is also consistent with Kawase et al. (2009), who indicated that, based on their pseudo global warming downscaling method, the Baiu rainband in June (the former half of the Baiu season) will shift southward in the future, although results of Kusunoki et al. (2006) and Kusunoki and Mizuta (2008) do not have such a clear tendency in June. Menon et al. (2002) and Ramanathan et al. (2005) point out that historical aerosols largely influence precipitation in South and East Asia. We may need to keep in mind influences of aerosols when we discuss possible anthropogenic influence on the historical trends. Further analysis is needed to reveal observed long-term climate changes in the summer season, using sunshine duration and sea level pressure data at stations and long-term re-analysis data over the 20th century.

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Supplement

Table S-1 is a list of stations used in this study.

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