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Distribution of seasonal rainfall in the East Asian monsoon region

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With 10 Figures

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Summary

This study deals with the climatological aspect of seasonal rainfall distribution in the East Asian monsoon region, which includes China, Korea and Japan. Rainfall patterns in these three countries have been investigated, but little attention has been paid to the linkages between them. This paper has contributed to the understanding of the inter-linkage of various sub-regions. Three datasets are used. One consists of several hundred gauges from China and South Korea. The second is based on the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP). The two sources of precipitation information are found to be consistent. The third dataset is the NCEP/NCAR reanalysis 850-hPa winds.

The CMAP precipitation shows that the seasonal transition over East Asia from the boreal winter to the boreal summer monsoon component occurs abruptly in mid-May. From late March to early May, the spring rainy season usually appears over South China and the East China Sea, but it is not so pronounced in Japan. The summer monsoon rainy season over East Asia commonly begins from mid-May to late May along longitudes of eastern China, the Korean Peninsula, and Japan. A strong quasi-20-day sub-seasonal oscillation in the precipitation appears to be dominant during this rainy season. The end date of the summer monsoon rainy season in eastern China and Japan occurs in late July, while the end date in the Korean Peninsula is around early August. The autumn rainy season in the Korean Peninsula has a major range from mid-August to mid-September. In southern China, the autumn rainy season prevails from late August to mid-October but a short autumn rainy season from late August to early September is noted in the lower part of the Yangtze River. In Japan, the autumn rainy season is relatively longer from mid-September to late October.

The sub-seasonal rainfall oscillation in Korea, eastern China and Japan are explained by, and comparable to, the 850-hPa circulation. The strong westerly frontal zone can control the location of the *Meiyu*, the *Changma*, and the *Baiu* in East Asia. The reason that the seasonal sea surface temperature change in the northwestern Pacific plays a critical role in the northward advance of the onset of the summer monsoon rainfall over East Asia is also discussed.

1. Introduction

The East Asian monsoon is well distinguished with two subsystems, i.e., a winter and a summer component in this region covering the area from China to Japan (Lau, 1992). The component of the east Asian summer monsoon (EASM) was widely investigated by many studies (Kao and Hsu, 1962; Lee, 1974; Tao and Chen, 1987; Ninomiya and Murakami, 1987; and others) based on land surface precipitation. Lau (1992), Matsumoto (1992) and Ding (1992) summarized the results of the EASM in more detail.

It was found that there are several outstanding rainy seasons from boreal spring to autumn in East Asia. Each country has given these rainy seasons a different name. The rainy season in spring from March to April in South China is called the pre-rainy season (Bao, 1987) or the spring persistent rains (Tian and Yasunari, 1998). Ding (1992) named the pre-summer rainy season from April to June in South China. Chen et al. (1992) mentioned that the onset of the *Meiyu* rainy season in general begins in South China in mid-May. In the study of eastern China monsoon rainfall, Lau et al. (1988) used the observed precipitation of longitudes between 100° E and 115° E, and Tian and Yasunari (1998) between 110° E and 120° E. From these investigations, the duration and region of the spring rainy season in China have not yet been clearly determined.

In summer, the rainy season, called the *Meiyu* in eastern China, the *Changma* in Korea and the *Baiu* in Japan, is one of the seasonal and climatic phenomena, which are characterized by an outstanding rainy spell in the East Asian region. Lau and Yang (1997) documented many onset stages during the march of the EASM from the South China Sea (SCS) to the Yellow Sea. They described that after the onset of the SCS summer monsoon, the Indian (South Asian) summer monsoon gradually advances from the south to the north of the Indian subcontinent in mid-June. Subsequently, as the Indian monsoon enters its mature phase, the rain belt of the *Meiyu* over the lower Yangtze River valley and the *Baiu* over Japan appears with slightly different onsets (Tao and Chen, 1987; Matsumoto, 1988). After that, the rain belt migrates northward from the Yangtze River to the lower Yellow River valley and Korea, which is referred to as the *Changma* in Korea (Lee, 1969; Lee and Kim, 1992; Kang et al., 1999). These processes of the EASM march are mainly based on the analyses of in-situ and satellite observations, but the sub-seasonal precipitation oscillations and connections between them in various sub-regions are still not completely understood.

In autumn, there is also a rainy season, called the *Kaul Changma* (autumn rainy season) in Korea, the *Qiu-yu* in China and the *Shurin* in Japan. The autumn rainy season in Japan is more obvious than in China and Korea, and many studies on these rainy seasons have been done in Japan (Suda and Asakura, 1955; Kimura, 1966; Marakami et al., 1962; Maejima, 1967; and others). In Korea, previous studies mainly used precipitation data of several surface stations to investigate the annual and autumn rainfall (Lee 1969; Lee, 1974; and others). In China, Kao and Kuo (1958) illustrated the autumn rainy area. All these autumn rainy seasons, in various sub-regions over East Asia, need to be compared in more detail through homogenous datasets.

From the previous studies, we understand that there are mainly three rainy seasons in East Asia. Because of the limitation of precipitation data, the natural seasons of rainfall were only documented in regional areas (Kao and Hsu, 1962; Maejima, 1967). In recent years, satellite observations, such as the outgoing longwave radiation (OLR), the blackbody temperature (Tbb) and the upper tropospheric water vapor (UTWV) have been applied to the study of EASM on a large-scale area (Matsumoto, 1992; Qian et al., 1998). From previous work (Qian and Lee, 2000), it was confirmed that OLR could only reveal well the convective precipitation over the tropical areas but were biased in the subtropical regions (Murakami, 1980; Lau et al., 1988). Due to the limitation of datasets, understanding the seasonal transitions and rainfall stages in various subregions as well as the connection and independence of rainfall from these subregions over East Asia is still unclear. Thus, to reveal the temporal-spatial distribution of the natural seasons in eastern Asia, a new dataset, which can well present the rainfall characteristics from a global-scale scope, is necessary.

In this study, summer and winter monsoon components, rainy seasons and sub-seasonal oscillations corresponding to precipitation, mainly for spring rainy, summer rainy and autumn rainy seasons in various subregions over East Asia will be investigated. Two precipitation datasets, the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) and the gauges in China and South Korea are used. The CMAP is also used to calibrate against the regional precipitation measurement in China and South Korea. To explain the seasonal precipitation feature the dataset of the NCEP/NCAR 850-hPa reanalysis winds (Kalnay and Coauthors, 1996) are also used.

After this introduction the two precipitation datasets and analysis method used in the paper are described in Section 2. The precipitation features derived from gauge observations are illustrated in Section 3. The seasonal transition and sub-seasonal oscillation derived from the CMAP precipitation are displayed in Section 4. The zonal march of the precipitation across the East Asian region is shown in Section 5. The spatial distribution of the summer monsoon precipitation in East Asia that separates from the tropical precipitation is depicted in Section 6. Finally, the conclusion and the discussion are given in Section 7.

2. Dataset and method

2.1 CMAP data

One of the datasets used in this study is pentad mean global precipitation from the CMAP data, which was constructed from rain gauge observations, satellite estimates and numerical model outputs (Xie and Arkin, 1997). The CMAP data for the period from 1980 to 1995 are analyzed with the pentad precipitation at the grids of 2.5 degrees. In previous work (Ding and Liu, 2001), the onset of the South China Sea (SCS) summer monsoon starts from mid-May. At that time, the precipitation of CMAP abruptly increases from about 4 mm/day in pentad 27 to 8 mm/day in pentad 28 (Qian and Lee, 2000), so that the criterion of deep convective precipitation has been determined as approximately 5–6 mm/day. In this paper, we choose 6 mm/day as the criterion of deep convective precipitation in East Asia.

2.2 Gauges in China and South Korea

Monthly and daily precipitation data in China from 1951 to 1991 are used in this paper. Observed daily surface precipitation for about 336 stations in early years and 361 stations in later years are applied to interpolate each year's longitude–latitude grid-point precipitation with one-degree horizontal resolution over China. The distribution of observed stations for the precipitation could be found in the work of Zhai et al. (1999). Many stations are located at the Yangtze River and the Yellow River valleys as well as southern China and northeast China but few over the western Tibetan Plateau covering the area of 80°–96° E and 29°–37° N. The daily precipitation data are obtained from 58 stations in South Korea from 1969 to 1998.

The rainfall observation in China and South Korea is used to compare with the CMAP regionally and sub-seasonally. From the daily rainfall, a five-day mean (73 pentads a year) and a monthly mean are calculated and used to describe the seasonal evolution of rainfall. The monthly rainfalls are made to obtain the climatological mean or the composite of several months. To describe the different characteristics of the monsoon rainfall evolution, temporal-spatial distributions of precipitation are given.

3. Precipitation feature

Generally, summer monsoon rainfall in China is concentrated in about three months from June to August. Figure 1 shows the climatological mean precipitation for three months (June, July and August) based on the China gauge observations from 1951 to 1991 (Qian et al., 2002). A high precipitation area exists not only in the southern and eastern coastland but also in the upper Yangtze River (100°–105° E) with relatively less precipitation in the central southern inland. Four maxima (heavy solid lines) of rainfall can be identified in the rain distribution: far northwest China (80°–90° E), the upper Yellow and Yangtze Rivers (100°–105° E), the eastern coastland (115°–120° E), and northeast China (near 125° E). Relatively less precipitation can be noted in the desert regions of northwest China, the central Yellow and Yangtze Rivers, and the western part of northeast China. Obviously, the precipitation count of less than 400 mm persists in the central south of the Yangtze River (110°–115° E). Comparing the two maxima of precipitation in the upper and lower parts of the Yangtze River valley, the largest rainfall center does not appear in the lower part but in the upper part.

From the summer rainfall distribution (Fig. 1), relatively less-precipitation lines naturally divide the major rainfall areas. The relatively high precipitation areas in the western Xinjiang Autonomous region, the eastern Tibetan Plateau, the eastern coastland, and northeast China can be identified. Among these four areas, the high precipitation is located in the upper parts of the Yangtze and the Yellow Rivers. This spatial distribution of summer precipitation implies that the different circulation systems may exist in eastern China and the upper parts of the rivers.

To examine the seasonal variation of summer rainfall in central China, particularly along the

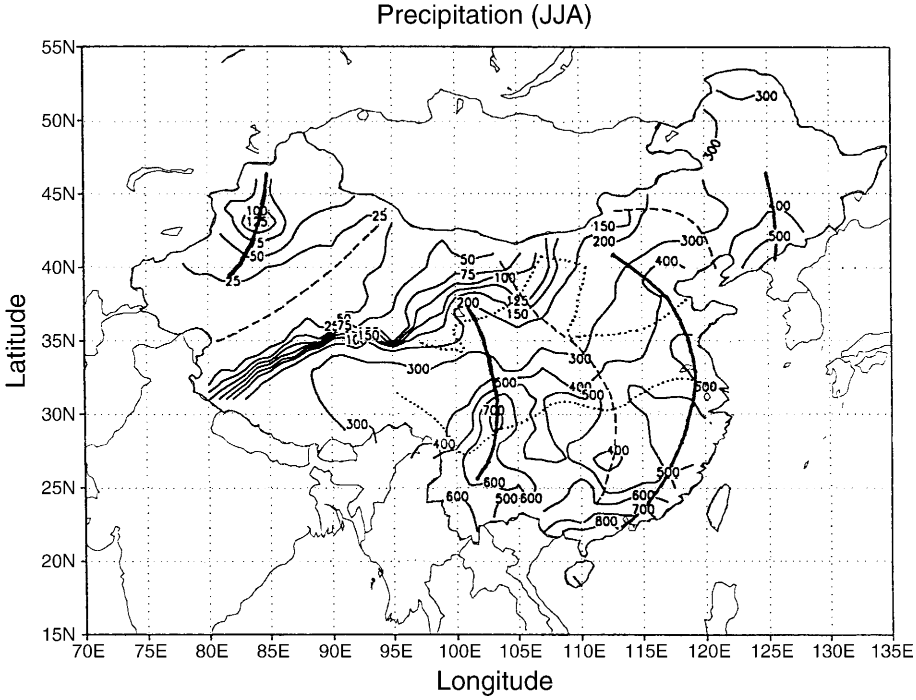

Fig. 1. Climatological mean precipitation (mm) for summer (June, July, August) over mainland China based on gauge precipitation for 1951 to 1991. Heavy solid lines denote the rainfall maximum and light dashed lines denote the relatively less-precipitation zones. Dotted lines indicate the Yellow River in north and the Yangtze River in south

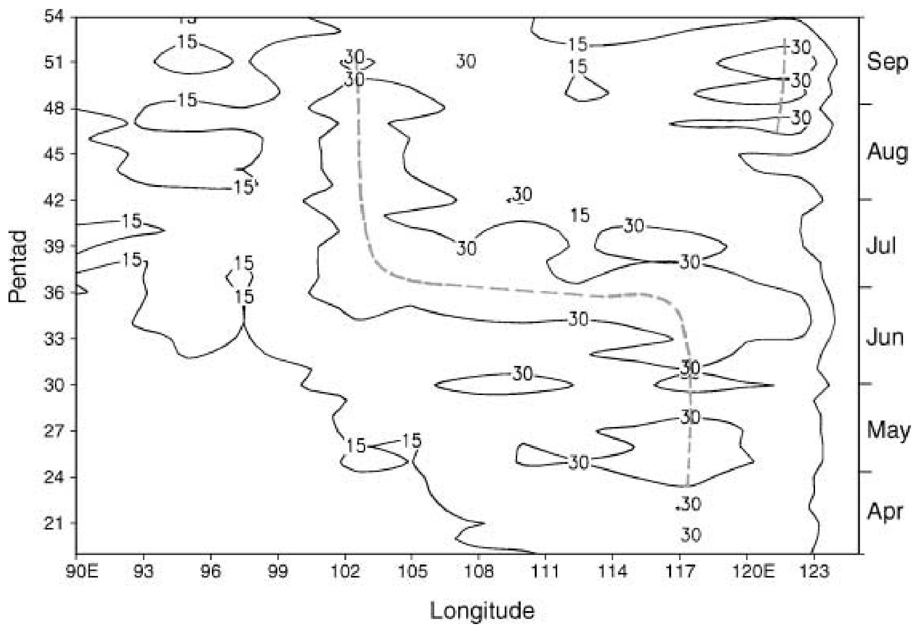

Fig. 2. Time-longitude section of pentad mean precipitation (mm/pentad) averaged over 29°–31° N, with time from April to September and longitude from 90°–123° E, based on the China gauge precipitation from 1979 to 1990. Heavy dashed lines indicate the rainfall maximum

Yangtze River, the time-longitude section of precipitation averaged between 29° N and 31° N was constructed (Fig. 2). We pay attention to the precipitation of more than 30 mm per pentad. The first precipitation period is from late April to mid-May near 117° E in the lower Yangtze River. After a short intermission, the second rainy period appears in the lower Yangtze River from early June to mid July with several fluctuations in the precipitation strength. At the same time, intensive precipitation in the wide longitudinal range occurs along the whole of the Yangtze River from mid June to mid July, which is the *Meiyu* season (Ding, 1992). From late July to late August the precipitation is climatologically less in the lower Yangtze River. The third rainy period is observed in the lower Yangtze River. The location of the third rainy period, associated with the typhoon rainfall fluctuations, is in the east relative to the previous two rainfall periods.

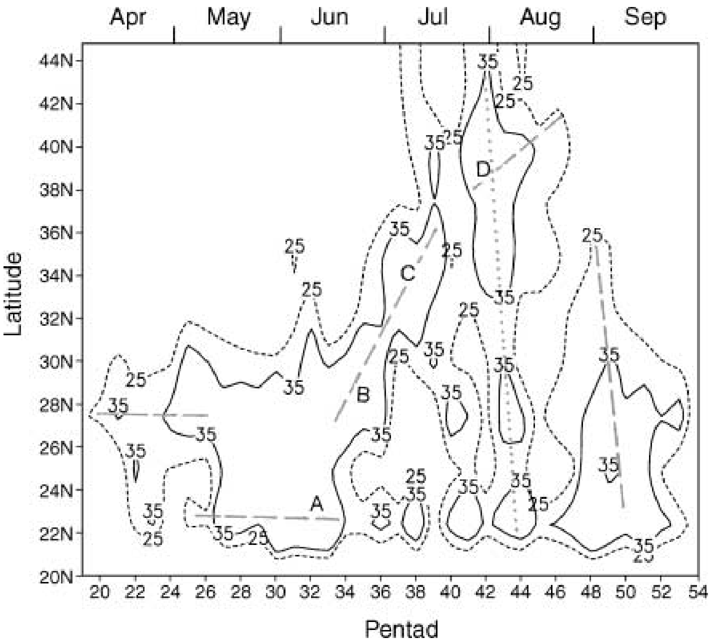

Fig. 3. Time-latitude section of pentad mean precipitation (mm/pentad) averaged over 115°–125° E with time from April to September and latitude from 20° N to 44° N, based on China gauge precipitation from 1979 to 1990. Heavy dashed lines indicate the rainfall maximum. A heavy dotted line denotes the large rainfall near pentad 43. Letters "A", "B", "C", "D" denote the four subseasonal oscillations

It is noted that the spring rainy season, the summer *Meiyu* and the *Qiu-yu* in the lower Yangtze River are clearer. In the middle part of the Yangtze River, the spring rainy season and autumn rainy season are not identified so clearly as that in the lower part. A long rainy season from mid June to mid September can be identified in the upper Yangtze River without intermission.

According to this rainfall distribution (Fig. 2), three longitudinal sections along the Yangtze River valley can be divided, these are the upper part from 100° E to 105° E, the middle part 105°–115° E and the lower part 115°–125° E. The time-meridional distribution of rainfall in the lower part of the Yangtze River is shown in Fig. 3. Five stages of rainfall advances or jumps are distinguished from spring to autumn. The first stage appears in the south of the Yangtze River near 28° N. In the second stage, broad-area rainfall is found from mid May to mid June (pentad 27–33) over southern China (the south of the Yangtze River). This broad-area rainfall mainly starts after the onset of the SCS monsoon maintaining up to mid June. Then the rainfall maximum moves rapidly northward from mid June in the lower Yangtze River to early July in the Huaihe River, which forms the third stage (pentad 33–39) of the rainfall. In mid July, there is an intermission (around the pentad 40) of rainfall in the strength. From late July to early August, the fourth rainfall stage occurs in northern China (the lower Yellow River). In mid August, another intermission (pentad 46–47) in rainfall strength takes place in the lower part of the Yangtze River. The autumn rainfall or the fifth stage of rainfall starts from late August to September in the lower Yangtze River and southern China (Kao and Kuo, 1958), which should be linked with the rainfall caused by typhoons.

Time-meridional distribution of the precipitation can be summarized as follows. The seasonal march of precipitation from spring to autumn in the lower Yangtze River or eastern China (the east of 115° E) is different from that in the middle and upper part of the river. Before mid May the spring rainfall appears in southern China. After the SCS summer monsoon onset, the summer monsoon rainy season is formed when the broad-area rainfall emerges in the south of the Yangtze River and northward traveling rainfall occurs from mid June in the lower Yangtze River to mid August in north China. In the summer monsoon rainy season, three stages of rainfall evolution can be clearly identified. The autumn rainy season is noted in eastern China and South China from late August to mid September.

To further identify the characteristic of rainfall advances over China in the period from May to July, Fig. 4 shows the monthly rainfall difference based on the China monthly dataset from 1951 to 1991. It is clearly seen (Fig. 4a) that increased rainfall in June compared to that in May appears

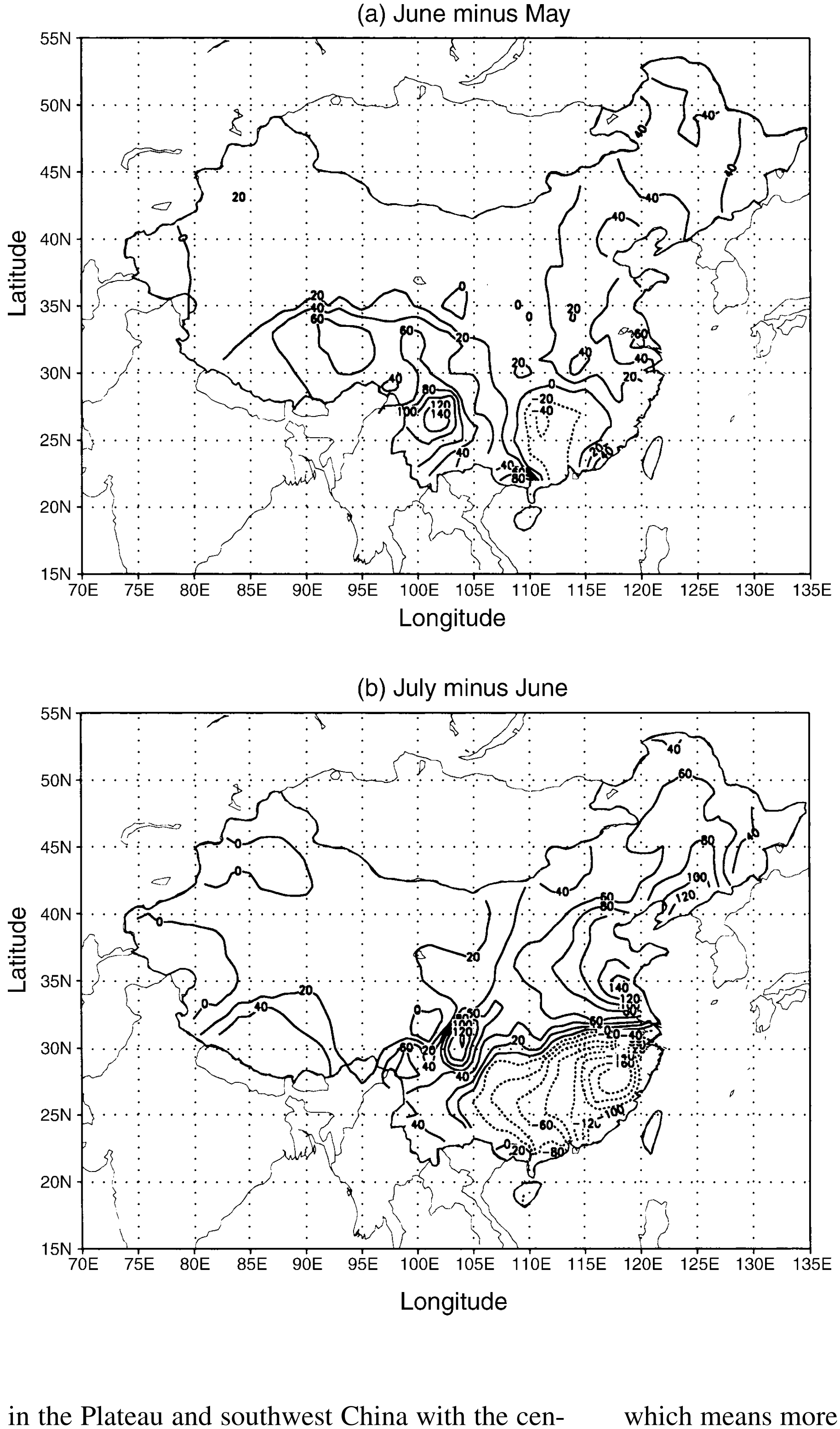

Fig. 4. Climatological rainfall differences (**a**) between June and May, and (**b**) between July and June, based on China monthly data from 1951 to 1991. The unit is mm

in the Plateau and southwest China with the center in the upper reaches of the rivers. Another area of increased rainfall is along the eastern coastland with the center in the lower Yangtze River. There is no obvious increase of rainfall in the central part of China. A negative area occurs in the central south of the Yangtze River, which means more precipitation in May. The tremendous change can be found where the negative area appears in South China (Fig. 4b), but positive centers are found in the upper parts and the north of the lower Yangtze River separately. This difference in July and June shows that the increased rainfall has migrated to the north of the

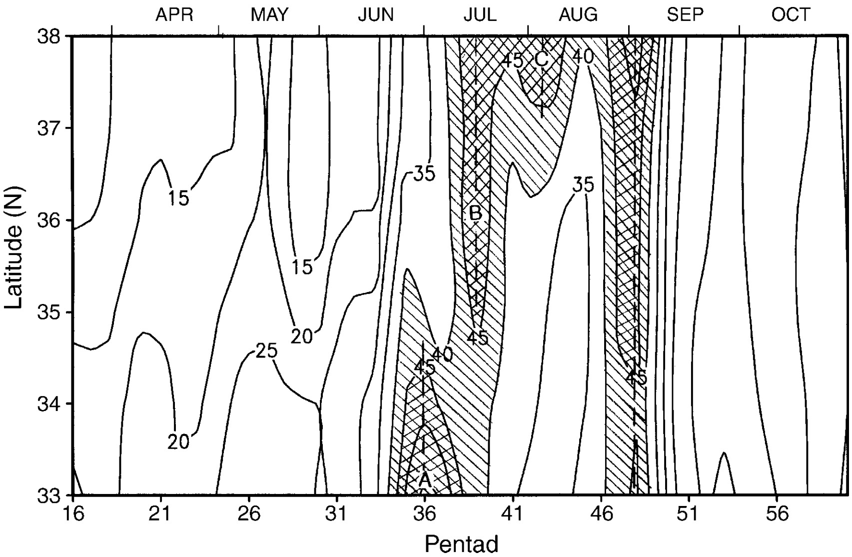

Fig. 5. Time-latitude section of pentad precipitation (mm/pentad) averaged over South Korea with time from April to October and latitude from 33°–38° N, based on Korea gauge precipitation from 1969 to 1998. Dashed lines indicate the rainfall maximum. Letters "A", "B" and "C" denote the three subseasonal oscillations

lower Yangtze River in July compared to that in June while the rainfall is steadily increasing at the upper parts.

Up to now, it should be recognized that the summer rainfall in the upper parts is completely different from that in eastern China. The difference may be the various rainfall systems with the different northward-extending velocities, appearing in the eastern coastland and the upper parts, separately. The strength of rainfall increase is larger in the upper parts than that in the east coastland during the northward advance.

Figure 5 shows the distribution of climatological pentad (5-day) precipitation in the time-latitude section in South Korea. We pay attention to precipitation of more than the 45 mm per pentad. It is clearly identified that several rainfall fluctuations from summer to autumn occur in South Korea. During late June and early July, a fluctuation appears over the Cheju Island. In mid July, a maximum of precipitation shifts northward to the south part of the peninsula. This is the northward advance or jump of the monsoon rain belt over the south part of the peninsula. In early August the rainfall maximum reaches the north part. Hence, three subseasonal fluctuations of precipitation with each fluctuation period about 20 days have been noted in the summer monsoon rainy season. After late August and early September, another precipitation maximum takes place in the peninsula from south to north associated with the retreat of the monsoon rain belt and typhoon activities, which forms the autumn rainy season in Korea.

4. Seasonal transition and sub-seasonal oscillation

To calibrate the CMAP data against the gauge observations and to understand the rainy seasons in a large-scale scope, the distributions of time-latitude CMAP precipitation from the pentad 1 to the pentad 73 of the year are constructed (Fig. 6). The precipitation of CMAP averaged between 115° E and 120° E along eastern China (Fig. 6a) is characterized as follows. A major precipitation maximum exists accompanying an annual cycle (heavy dashed line) crossing the equator from south to north in mid May and from north to south in the end of November. After mid May, the large precipitation (more than 6 mm/day) extends northward covering eastern China in wide latitudes while the deep convection ceases in the Southern Hemisphere. Therefore, the seasonal transition from the boreal winter monsoon component to the boreal summer monsoon component can be determined in mid May in China. Before the onset of the SCS summer monsoon, precipitation of more than 6 mm/day appears from mid March to early May over South China (25°–30° N), which is the so-called pre-rainy season (Bao, 1987) or persistent spring rain period (Tian and Yasunari, 1998) in China. From mid June to late July, the precipitation maximum shifts northward from the lower Yangtze River valley (28°–32° N) to the Huaihe River valley (32°–35° N) and northern China. The concentrated precipitation from mid June to July is called the *Meiyu* in the lower Yangtze River. From late July to late August is the period of dry and hot summer in the lower Yangtze River. Two short rainfall periods emerge at the end of August and early September, which are called the *Qiu-yu* in the lower Yangtze River valley by local inhabitants. In eastern China, three rainy seasons: spring rainy season, summer rainy season and autumn rainy season are distinguished (marked in the left of Fig. 6a), which are similar to those shown in Fig. 3. During the summer rainy season, there are several oscillations in precipitation magnitude over the lower Yangtze River.

Along the longitudes between 125° E and 130° E, where the Korean Peninsula is located (Fig. 6b), the seasonal component transitions

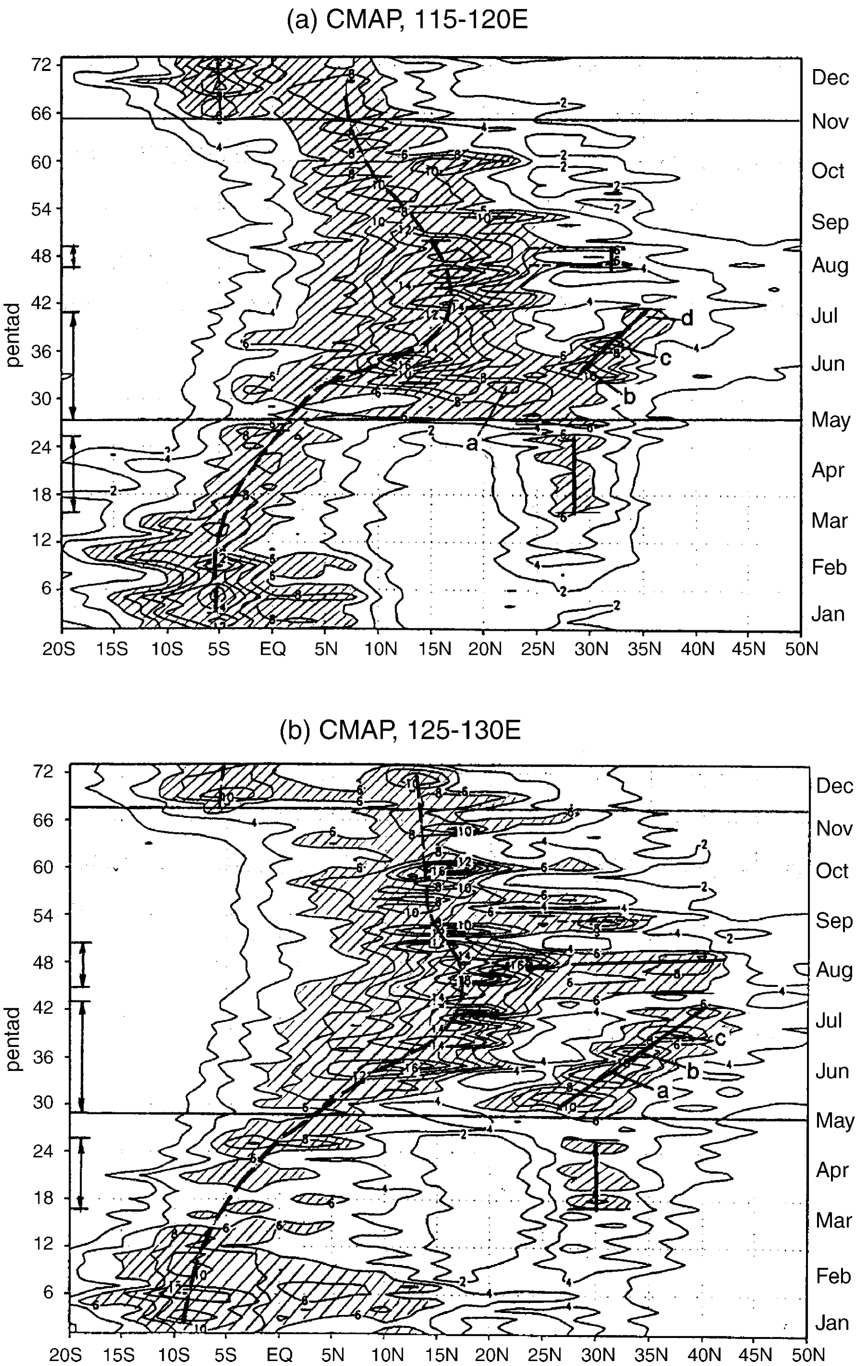

Fig. 6. The pentad-latitude section of CMAP precipitation (mm/day) averaged the longitudes (**a**) 115–120° E, (**b**) 125–130° E, and (**c**) 130–140° E for pentads 1–73 of the year. Shaded areas denote the precipitation more than 6 mm/pentad. Dashed lines indicate the tropical precipitation maximum and solid lines denote the East Asian precipitation maximum. Arrow lines in the left side indicate the rainy periods in East Asia. The small letters in (**a**) and (**b**) denote the subseasonal oscillations

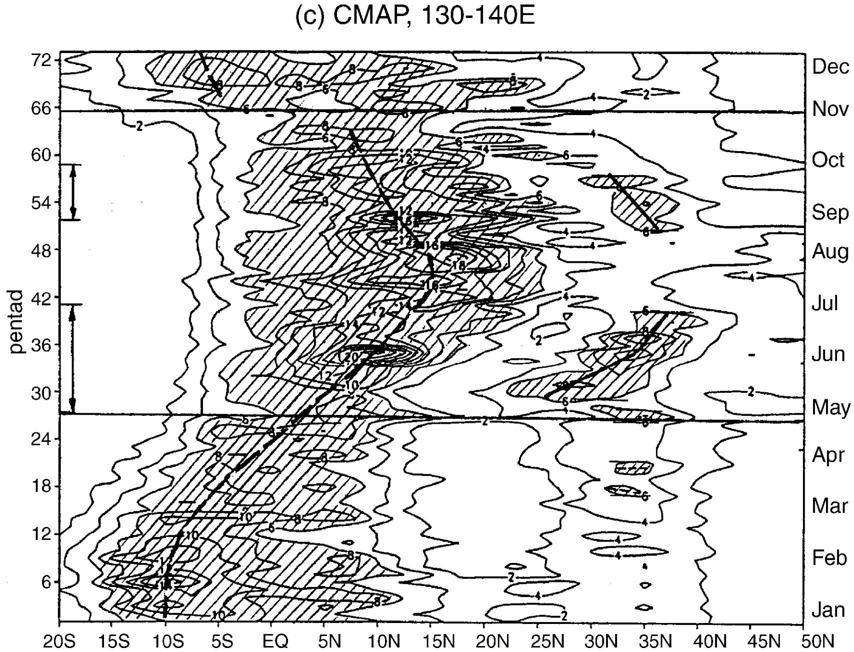

Fig. 6 (*continued*)

take place in late May and early December. Before the seasonal transition starts in late May, the major precipitation in the Northern Hemisphere remains over the East China Sea around 30° N from late March to mid May, which is the spring rainy season. After the seasonal component transition, local maximum precipitation between 20° N and 40° N shifts northward from late May to early August with several sub-seasonal oscillations. Two oscillations (the first and the second from late May to June) appear in the East China Sea. Considering South Korea that is located mainly over 33°–38° N, another two oscillations (the third and the fourth) of rainfall appear from late June to mid-July, which remarkably coincide with those shown in Fig. 5. The last oscillation with the center in early August is located in North Korea. The fluctuation from late August to September is the autumn rainfall or the *Kaul Changma* crossing the whole of the Korean Peninsula. Three rainy seasons along the longitudes of 125°–130° E are also distinguished (marked in the left of Fig. 6b). Along those longitudes, the *Changma* breaks from the south of the Korean Peninsula in early June and ends from the northern part of the peninsula in early August. The spring rainy season only appears in the south. The sub-seasonal oscillations of the precipitation with each oscillation period of about 20 days along these longitudes in summer rainy season are outstanding.

The majority of Japan is located between 130°–140° E and 30°–40° N. According to the precipitation along the longitudes between 130° E and 140° E (Fig. 6c) in southern Japan, two short periods with rainfall of more than 6 mm/day are noted in early and mid April so that there is no remarkable spring persistent rains in Japan. The seasonal component transitions are found in mid May and late November. Over the latitudes of Japan, the *Baiu* and the *Shurin* are clearly distinguished from mid May to late July and from mid September to late October respectively with a dry period from late July to mid September. In the *Baiu* period, the precipitation of more than 6 mm/day starts from southern Japan in early June, then progressively moves to the northern part in late July. According to the CMAP precipitation, there are only two rainy seasons over the Japanese islands.

Time-latitude distribution of the CMAP precipitation in East Asia indicates that the periods of two monsoon components can be divided. The summer monsoon component begins from mid May and ends in late November while the winter monsoon component is from late November to mid May. Within the summer monsoon component, there are two rainy seasons in East Asia.

The first rainy season with the northward traveling rain belt is the so-called *Meiyu* in China, the *Changma* in Korea, and the *Baiu* in Japan. The *Qiu-yu* in China, the *Kaul Changma* in Korea, and the *Shurin* in Japan are the second rainy season in East Asia with the southward traveling rain belt. The first rainy season is more obvious than the second when we compare their period and strength. The autumn precipitation in Japan is as long as that in Korea but begins about one month later than that in Korea. Within the period of winter monsoon component, there is quasi-stationary rainfall in southern China and the East China Sea from mid March to early May, which is the spring rainy season. The rainfall and its seasonal evolution in East Asia are separated from those in the tropics, depicted by different heavy dashed lines (Fig. 6).

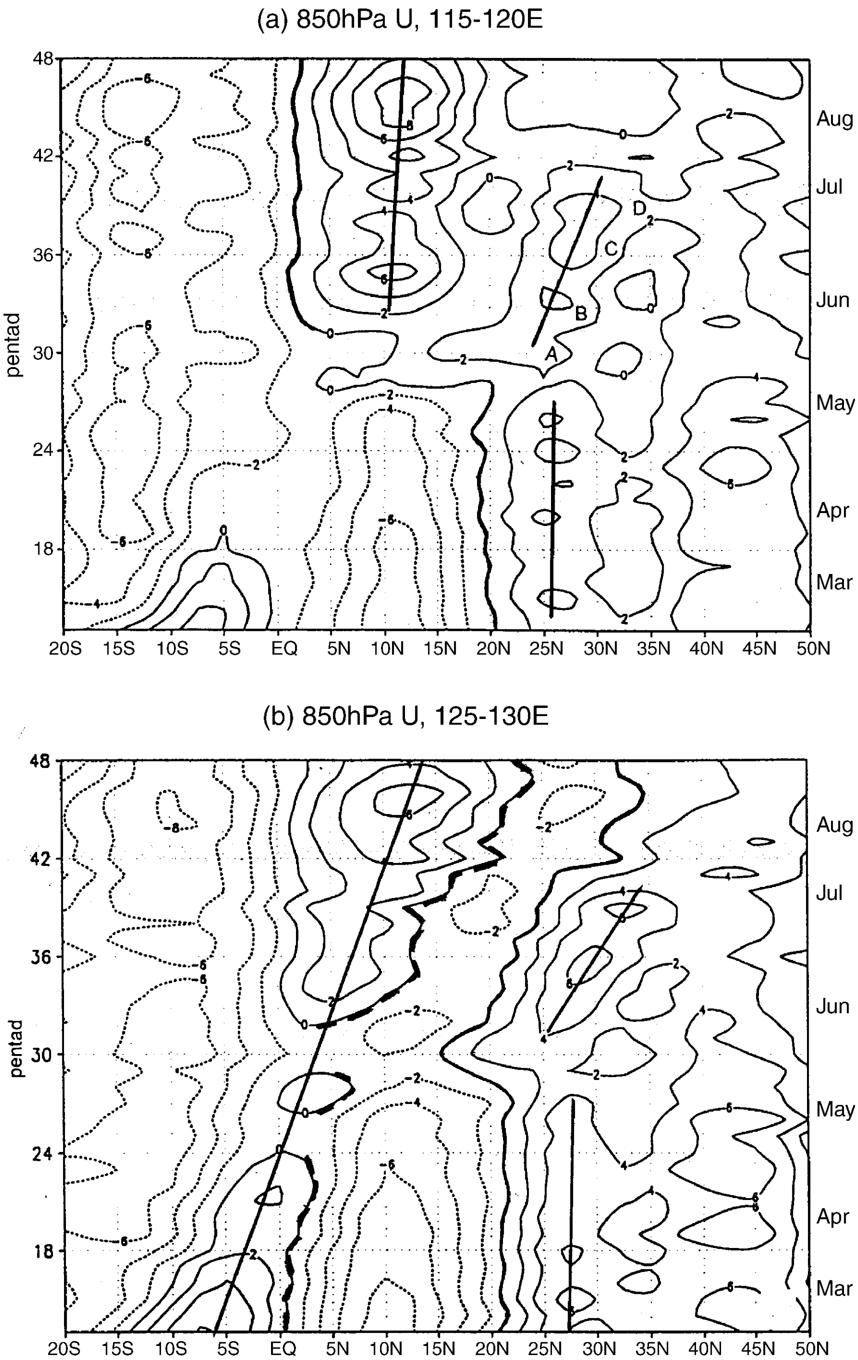

Fig. 7. The zonal wind mean (m/s) at 850-hPa level along the longitudes (**a**) 125°–130° E, (**b**) 115°–120° E and (**c**) 130°–140° E, respectively. The capital letters in (**a**) denote the subseasonal fluctuations. The heavy solid lines indicate the westerly maximum and the heavy solid curves indicate the ridgeline of the subtropical high. The heavy dashed lines denote the westerly zero line in the tropics

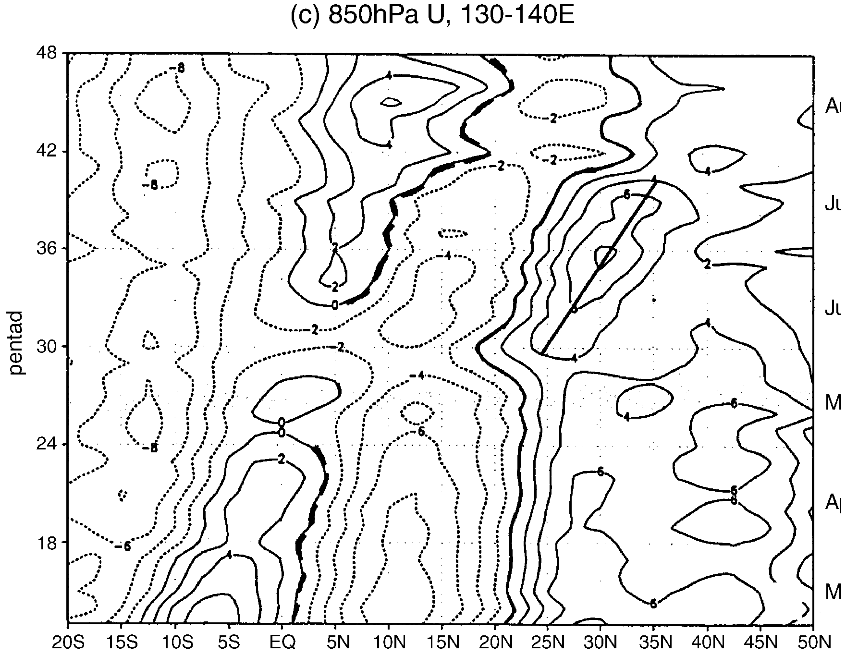

Fig. 7 (*continued*)

The northward-advance period of the East Asian summer monsoon is obviously identified from mid May to July. The latitude-pentad distributions of 850-hPa zonal winds along the longitudes 115°–120° E, 125°–130° E, and 130°–140° E were shown in Fig. 7 for the period. Along the longitude between 115° E and 120° E (Fig. 7a), the ridgeline of the subtropical high is maintained in 20° N up to the SCS summer monsoon onset (pentad 28). Before mid May the relatively strong westerly wind are maintained in South China. After the onset of the SCS summer monsoon, the westerly center shifts northward from 25° N to 30° N gradually. The major westerly center from mid June to mid July is consistent with the *Meiyu* (Fig. 6a) in eastern China. At the same time, a relatively strong prevailing westerly wind can been found over the South China Sea. The tropical westerly wind and the subtropical westerly wind are separated and distinguished clearly from the SCS to eastern China.

In Fig. 7b, the easterly wind is dominant between 5° N and 20° N by mid May. The heavy curve denotes the ridgeline of the subtropical high. Before mid May the ridgeline is stagnant in 21° N but in late May it shifts southward up to 15° N. After that it gradually moves northward up to 34° N in mid August and the fluctuations can be noted from June to July. The center of the strong westerly wind in mid latitude appears from early June to mid July, which is consistent with the major precipitation in the Korean Peninsula. This relationship between westerly wind and precipitation in Korea implies that there is a strong westerly frontal zone in summer.

The ridgeline of the subtropical high is stagnant to about 22° N (Fig. 7c). It shifts southward to the 18° N in late June then gradually moves northward to the 33° N at the end of July. The center of strong westerly wind from June to July is consistent with the precipitation in Japan. In late May, the ridgeline first shifts southward then gradually moves northward to late July so that the summer monsoon in this region prevails between late May and late July. Also, in June and July the subtropical westerly wind is separated from the tropical westerly wind in longitude. The subtropical high gradually migrates from south to north with several fluctuations.

5. Zonal distribution

The time-longitude distributions of the CMAP precipitation averaged between 25°–30° N, 30°–35° N and 35°–40° N are given in Fig. 8. In the latitudinal zone (25°–30° N, Fig. 8a), two regional maxima of quasi-stationary precipitation and three maxima of the traveling precipitation are clearly shown. In spring one maximum of quasi-stationary rainfall is located in the south of the lower Yangtze River. Another quasi-stationary rainfall maximum is situated in the north of India from June through September. Three major maxima of the traveling precipitation appear in East Asia. From mid May to early July, high precipitation first appears in eastern China then quickly extends eastward to the East China Sea while it slowly extends westward to western China. However, the maximum precipitation looks likely to first appear over the south of Japan, then the south of Korea and south China. Another precipitation maximum also

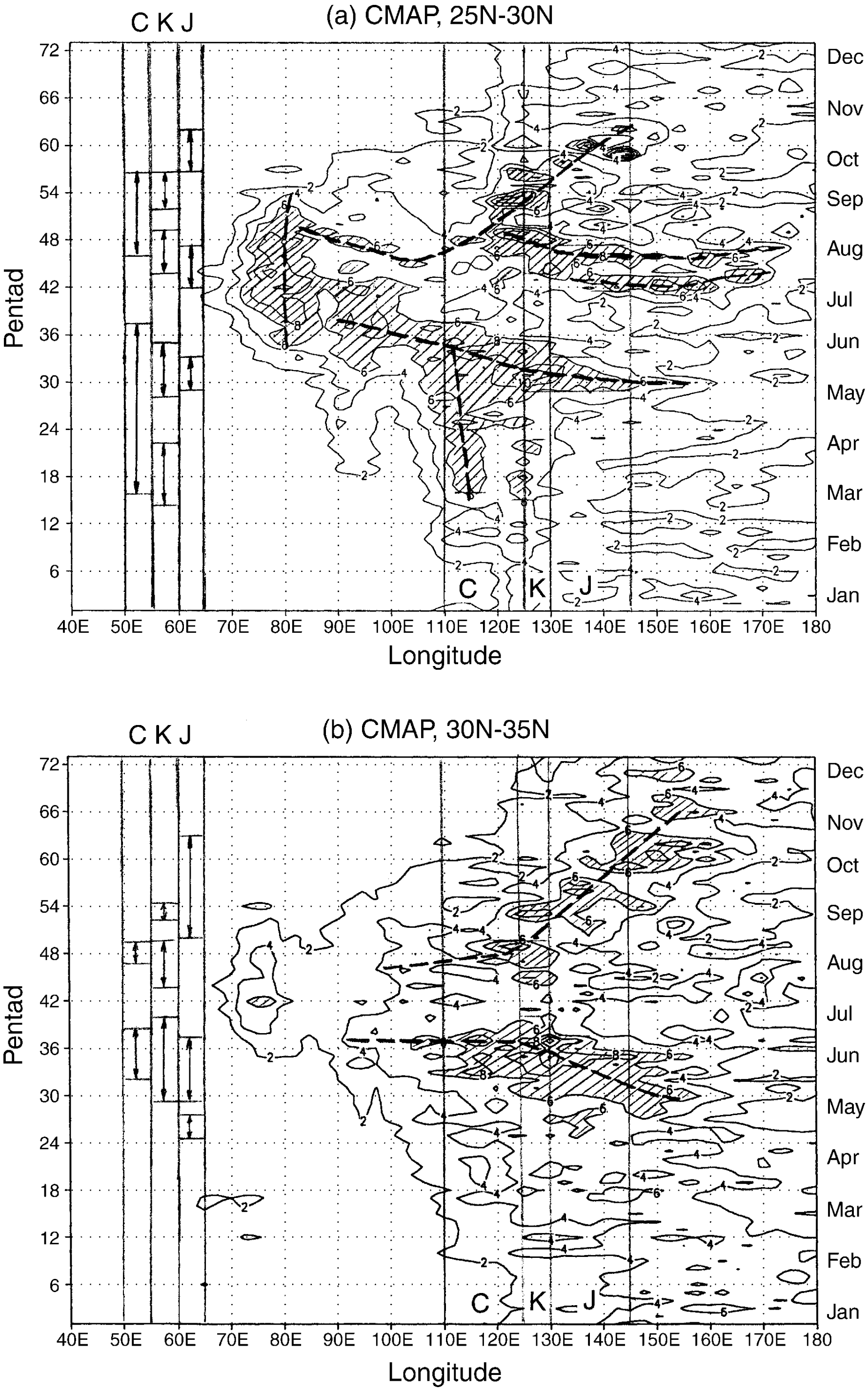

Fig. 8. Same as in Fig. 6 except the latitudes, (**a**) 25°–30° N, (**b**) 30°–35° N, and (**c**) 35°–40° N. Marks "C", "K" and "J" denote the longitudes crossing eastern China, the Korean Peninsula and Japanese islands. Dashed lines indicate the precipitation maximum

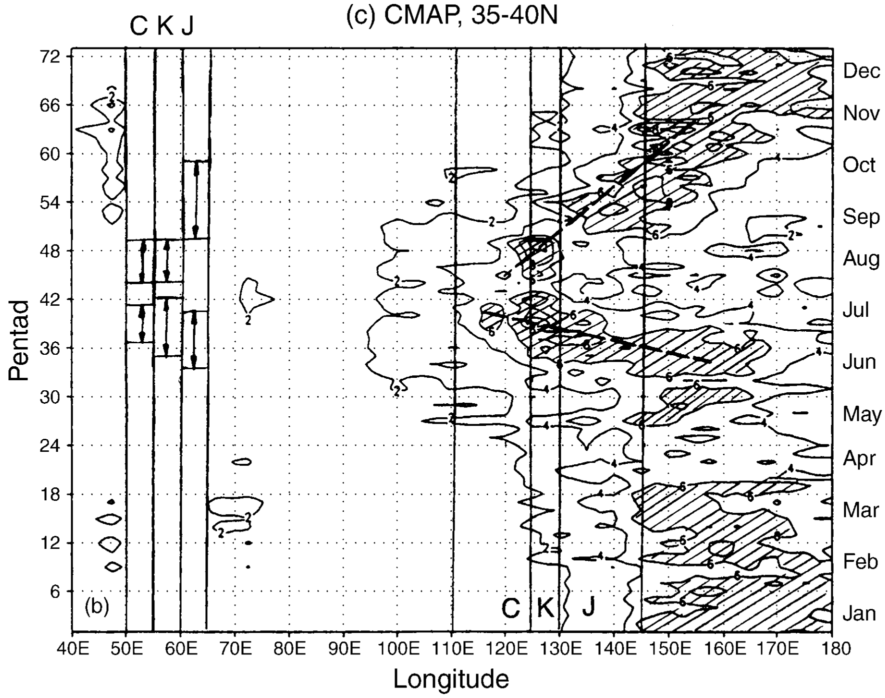

Fig. 8 (*continued*)

occurs first over the south of Japan in late July, then over the south of Korea and eastern China in August. Differing from the above, the other precipitation maximum first appears from eastern China in mid August, then over the south of Korea in late September and the south of Japan in mid October. A long continuous rainy period can be found over South China in the longitude of "C" from March through June and three outstanding rainy periods over the East China Sea ("K" and "J") from May to October. The periods in "C", "K" and "J" longitudes approximately indicating eastern China, Korea and Japan located, respectively, are marked in the left of Fig. 8a.

The rainfall distribution varies to a certain degree over the zone (30°–35° N, Fig. 8b). One rainfall maximum starts from mid May near the longitude 150° E, then over Japan and the south part of the Korean Peninsula in early June and eastern China in mid June. The autumn rainfall first appears from the southern part of the Korean Peninsula in August, then China in late August, and finally over southern Japan starting from early September. The autumn rainfall in southern Japan is the longest lasting about two months among the three regions. The *Kaul Changma* in the southern part of the Korean Peninsula exhibits two stages in mid August, and late September. The periods in "C", "K" and "J" longitudes are also marked in the left of Fig. 8b.

Along the zone between 35° N and 40° N (Fig. 8c), the precipitation distribution is similar to that of 30°–35° N but starts from mid June near the longitude 150° E, then over Japan in mid June, Korea in late June and the lower part of the Yellow River in early July. The autumn rainfall starts in the lower part of the Yellow River and Korea in mid August, then over Japan in mid September. In this zone, the summer rainy season (the *Changma*) in Korea is particularly longer than that in the lower part of the Yellow River. The autumn rainy season (the *Shurin*) in Japan is the longest and the last rainy period if it is compared to those in China and Korea.

The propagations of the maximum precipitation are simply displayed in the zone of 30°–35° N and the zone of 35°–40° N. During the summer rainy season the precipitation maximum shifts westward and it propagates eastward during the autumn rainy season. The termination period between the summer rainy season and the autumn rainy season is longer in lower latitudes than that in the higher latitude for the three counties. This is due to the subtropical high moving northward during the summer rainy season and retreats southward during the autumn rainy season.

6. Spatial distribution

From the latitudinal and the longitudinal variations of the CMAP precipitation, the major rainfall clearly appears during pentad 34–39 (11 June–14 July) in the process of the EASM march. Figure 9 shows the spatial distributions of the CMAP precipitation for this period. The major rainfall areas are notable over the tropical region and East Asia including central-eastern China, Korea and southern Japan. The rainfall, with several maxima (dashed lines in Fig. 9), extends northward from the tropical to subtropical regions, particularly along the upper and lower parts of the Yangtze River as well as Korea and Japan in East Asia. The rain of the *Meiyu* front or the rainfall of the EASM can be clearly seen from the Yangtze River to Japan, which is obviously separated from the tropical rainfall. From the comparison of precipitation distributions between Fig. 9 and Fig. 1, the CMAP precipitation can be applied to describe well the monsoon characteristics in China. If we plot the climatologically mean 850-hPa flows (figure omitted) for pentad 34–39, the subtropical high circulation controls less precipitation area over the northwestern Pacific. The ridgeline of the subtropical high stretches along 25° N so that the changes in the strength and the position of the subtropical high will charge the rain belt in East Asia.

To explain the precipitation distribution plotted in Fig. 1, the 850-hPa winds analyzed for the period 1951 to 1991 from June to August over the Asian region are shown in Fig. 10. We first focus on the region of China. In the summer period, southerly flows are predominant over eastern China. According to Li and Qu (1999), monsoon flows should come from the cross-equatorial flows. We adopt this view to judge whether a place is a monsoon region. Along the longitude of 110° E, southerly flows are rather strong in the south coast of China but there is a meridional divergence axis (heavy dashed-dotted line) of the flows over central China. This meridional divergence axis is perfectly consistent with less rainfall (Fig. 1) so that the meridional divergence axis divides the Yangtze River and the Yellow River into the upper parts and the lower parts. The monsoon southwesterlies are prevailing in the lower part. In the upper part, the southeasterlies prevail and converge along the east edge of the Plateau. Some southeasterlies, which come from the north of the Bay of Bengal (BOB), may be traced back to the cross-equatorial flows. It can be identified from Fig. 10 that the monsoon rain belt in the lower part is caused by southwesterly flows while the monsoon rain belt in the upper parts is led by

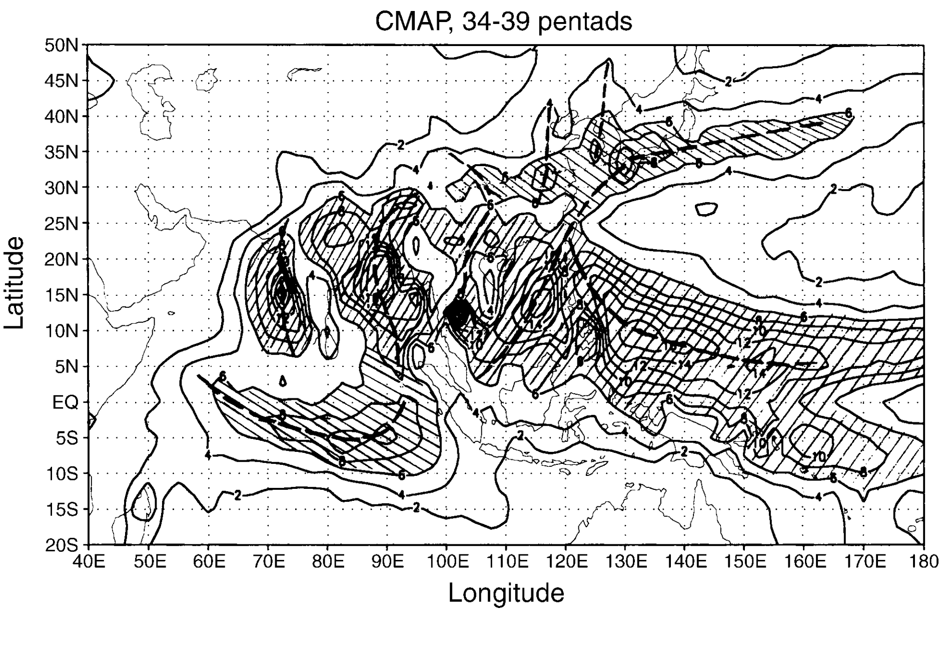

Fig. 9. Climatological mean precipitation (mm/day) in the period of pentads 34–39 (11 June–14 July), based on CMAP precipitation. The dashed lines indicate the precipitation maximum

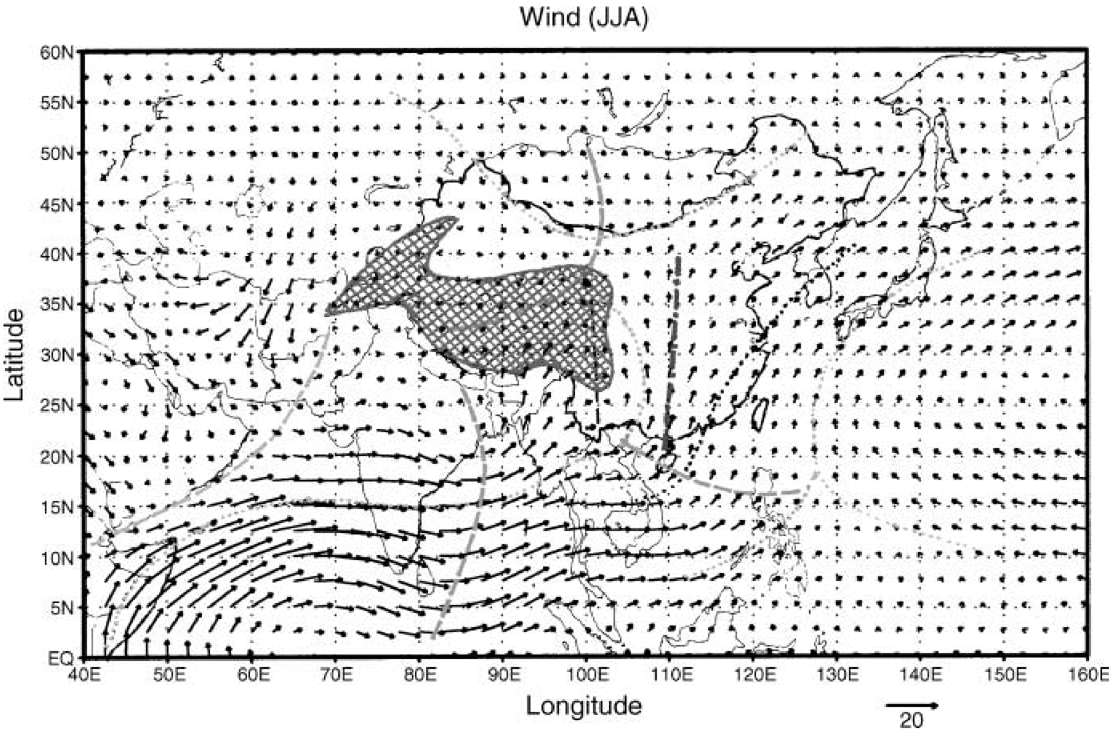

Fig. 10. Climatological mean 850 hPa-wind field (m/s) for three months (June, July, August). Dashed line indicates the monsoon trough (or convergent/divergent line) and the dotted lines indicate the streamline

southeasterly flows. This distribution of the 850-hPa flows in the three months may explain why the precipitation steadily increases in the upper parts of the two rivers. The rain belt moving northward in eastern China through several steps may be caused by the strength variations of the subtropical high. The major rain belt over East Asia in the pentads 34–39 is directly linked to the interaction between the southwesterly monsoon flow and the northwesterly flow.

7. Conclusion and discussion

This paper is a thorough description of the precipitation climatology in East Asia, based on two datasets. One consists of several hundred gauges from China and South Korea. The other is based on a combination of gauges and other information, mainly estimates derived from satellite observations. The two sources of information are found to be very consistent since the CMAP process relies strongly on gauge information. The seasonal transitions of the monsoon component and three rainy seasons (spring rainy season, summer monsoon and autumn rainy season) in the regional areas of East Asia are identified clearly and in detail by analyzing the CMAP precipitation. In the summer monsoon period, the temporal-spatial distributions of precipitation over East Asia can be explained by the 850-hPa winds. The major findings are summarized below.

(1) Two monsoon components are determined. The seasonal transition from the boreal winter monsoon component to the boreal summer monsoon component in East Asia takes place in mid-May while the reversed transition occurs in late November, accompanying the adjustments of rain belt in the Southern and the Northern Hemisphere. The summer monsoon rain belt gradually shifts northward from June to July while the autumn rainfall retreads southward from August to October in East Asia but the starting times in different regions vary.

(2) Because of the stagnation of the ridgeline of the subtropical high from March to mid-May (Qian and Lee, 2000), persistent rainfall forms over the south of the Yangtze River

and the East China Sea for about two months. This quasi-stationary rainfall in East Asia is called the spring rainy season, which occurs within the boreal winter monsoon component.

(3) After the onset of the SCS summer monsoon in mid May, two important facts can be observed in East Asia. One is that the spatial distribution of the precipitation in East Asia covering eastern China, the Korean Peninsula, and Japan is separated from the tropical precipitation for the summer monsoon period (pentad 34–39). Another is that the summer monsoon rain belt gradually migrates northward from June near 25° N to late July in 40° N with subseasonal (20-day) oscillations of northward traveling rainfall in strength. This period with northward traveling rainfall from south to north in East Asia is referred as the summer monsoon rainy season or the *Meiyu* in China, the *Changma* in Korea, and the *Baiu* in Japan.

(4) The spatial distributions and temporal oscillations of the precipitation in East Asia are dynamically linked to the 850-hPa winds in the widespread Asian-Pacific region. In China, the advances northward of the summer monsoon precipitation are different in the western part and along the eastern coast. The reason is that the southeasterly winds are steady strengthened in the eastern edge of the plateau, while the strength and the location of the southwesterly winds vary in the eastern China, the Korean Peninsula, and Japan, accompanying the subtropical high.

(5) Generally in August, the subtropical high of the western Pacific reaches the strongest stage and dominates East Asia. During this time, dry-hot weather prevails over East Asia. After that, the autumn rainy season starts over East Asia when the subtropical high withdraws southward. The longest and the latest autumn rainfall appears in Japan from mid September to late October. Two periods of autumn rainfall occur over the Korean Peninsula while the shortest autumn rainfall is found in eastern China. This period with mainly southward withdrawing rainfall is referred as the *Qiu-yu* in China, the *Kaul Changma* in Korea, and the *Shurin* in Japan.

Rainfall patterns of these three countries, including China, Korea and Japan, have been investigated separately, however, little attention was paid to the linkage between them from the temporal and spatial aspects. Such a comprehensive description of precipitation climatology is potentially of value in studying other aspects of climate in the region. In the following we will discuss the several aspects concerning the subseasonal oscillation in the summer rainy season, the circulation and the forcing of the precipitation variations.

(1) Subseasonal oscillation or intraseasonal oscillation (ISO) was derived from the gauge observations and the CMAP precipitation in East Asia during the summer rainy season. From early June to late July four fluctuations of the gauge precipitation in eastern China are denoted in Fig. 3 with the letters "A", "B", "C", and "D". Those fluctuations are also occupied in the CMAP precipitation with the same temporal-spatial distribution and indicated in Fig. 6a by the letters "a", "b", "c", and "d". Climatologically, those four fluctuations exist commonly and robustly in the Korean Peninsula and Japan but five fluctuations are observed in the section between the 125°–130° E longitudes from early June to early August. Among them three fluctuations can be compared from the gauge observations in South Korea (Fig. 5) and the CMAP in Fig. 6b that are indicated by three capital and small letters, respectively. An interesting phenomenon is that the northward propagating summer monsoon consists of several phase-lock wet oscillations. Therefore, the onset of the EASM occurs when a wet phase of the climatological intraseasonal oscillation arrives or develops. In the EASM region, the seasonal process and the ISO propagation are both northward as well as are interconnected in all subregions.

(2) As we know that the ISO is closely linked to the subtropical high or the circulation variations in the summer rainy season over East Asia. Accompanying the northward propagation of the subtropical westerly winds from early June to late July, the ISO can also be found in the strength of westerly winds in

East Asia. Four fluctuations in the westerly strength at the 850-hPa level are marked by the letters "A", "B", "C", and "D" in Fig. 7a. The fluctuations in the winds are coincidental to the ISO in the precipitation. Thus, the onset of the summer rainy season relies strongly on the ISO while the ISO depends on the activity of the subtropical high. The abruptness of the onset should be related to the atmospheric internal dynamics since the external forcing (solar radiation and sea surface temperature forcing) changes slowly (Wu and Wang, 2001).

(3) The climatological summer rainy season commences in low latitudes and advances poleward. The advance, however, is not purely meridional due to the effects of land and sea distribution (Wu and Wang, 2001). Over the BOB and the Indian subcontinent, the onset advances northwestward (Indian Meteorological Department, 1943). Over the northwestern Pacific, the onset displays distinct northeastward march (Wang, 1994; Murakami and Matsumoto, 1994). Over the East Asian region, the onset mainly advances northward (Tao and Chen, 1987; Lau and Yang, 1997). The onset process from all three directions are concerned with the extension of deep tropical convection seasonally over the eastern tropical Indian Ocean and the tropical western Pacific (Qian and Lee, 2000). It was speculated that annually varying sea surface temperature (SST) and SST gradients contribute to the march of the onset (Wang, 1994). Recently, the process that the SST variation affects such onset advance in the northwestern Pacific was deduced (Wu and Wang, 2001). They found that the seasonal SST change in the northwestern Pacific plays a critical role in the northeastward advance of the onset. The seasonal northeastward march of the warmest SST tongue (SST exceeding 29.5 °C) favors the northeastward movement of the monsoon trough and the high convective instability region. The seasonal SST change, in turn, is affected by the monsoon through cloud-radiation and wind-evaporation feedback. The monsoon trough is varied in the south of the eastern Asian monsoon region. Therefore, the onset of the EASM should be related to the SST change. On the other hand, the onset of the EASM may be strongly affected by the land–sea thermal contrast because the region is located in the eastern continent and the western ocean. Also, the interannual variation of the SST can influence the onset time. This suggests that the northward advance of the EASM onset is an interactive process. These seasonal rainy seasons and subseasonal oscillations are potentially of value in numerical modeling works.

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