Rainy Season of the Asian–Pacific Summer Monsoon*

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(Manuscript received 19 December 2000, in final form 13 July 2001)

ABSTRACT

To date, the monsoon-research community has not yet reached a consensus on a unified definition of monsoon rainy season or on the linkage between the onsets over the Asian continent and the adjacent oceans. A single rainfall parameter is proposed, and a suite of universal criteria for defining the domain, onset, peak, and withdrawal of the rainy season are developed. These results reveal a cohesive spatial–temporal structure of the Asian–Pacific monsoon rainy season characteristics, which will facilitate validation of monsoon hydrological cycles simulated by climate system models and improve our understanding of monsoon dynamics.

The large-scale onset of the Asian monsoon rainy season consists of two phases. The first phase begins with the rainfall surges over the South China Sea (SCS) in mid-May, which establishes a planetary-scale monsoon rainband extending from the south Asian marginal seas (the Arabian Sea, the Bay of Bengal, and the SCS) to the subtropical western North Pacific (WNP). The rainband then advances northwestward, initiating the continental Indian rainy season, the Chinese mei-yu, and the Japanese baiu in early to mid-June (the second phase). The heights of the rainy seasons occur primarily in three stepwise phases: in late June over the mei-yu/baiu regions, the northern Bay of Bengal, and the vicinity of the Philippines, in late July over India and northern China; and in mid-August over the tropical WNP. The rainy season retreats northward over east Asia, yet it moves southward over India and the WNP.

Clear distinctions in the characteristics of the rainy season exist among the Indian, east Asian, and WNP summer monsoon regions. Nevertheless, the rainy seasons of the three subsystems also show close linkage. The causes of the regional distinctions and linkages are discussed. Also discussed are the atypical monsoon rainy seasons, such as the skewed and bimodal seasonal distributions found in various places of Asian monsoon domain.

1. Introduction

Rainfall is an essential meteorological parameter describing the monsoon climate. Rainfall distribution indicates the location of the atmospheric heat source that drives tropical circulation; thus, rainfall variation reflects the variability of the entire monsoon circulation system. Rainfall is also a key component of the hydrological cycle of the earth's climate system, playing a central role in connecting terrestrial, atmospheric, and oceanic processes. The study of rainfall characteristics is of central importance for understanding monsoon circulation and its relationship with other components of the hydrological cycle.

The majority of the literature dealing with Asian monsoon rainfall climatology has been devoted to depicting rainy seasons over the land and islands using rain gauge observations (e.g., Yoshino 1965, 1966; Rao 1976; Ninomiya and Murakami 1987; Ding 1992; Chen 1994, and many others). Figure 1 shows summer monsoon onset dates determined by Tao and Chen (1987), Tanaka (1992), and Lau and Yang (1997), respectively. Over east Asia, the discrepancies among the results are significant due to use of different datasets and different definitions of the onset. In general, the onset and withdrawal dates of the summer monsoon rainy season have not been defined in a universal way over the entire Asian summer monsoon region.

Figure 1 also shows that our knowledge falls short about the rainy season over marginal seas of the Asian continent (such as the Arabian Sea, the Bay of Bengal, the South China Sea, and the east China Sea) due to a lack of long-term reliable observations. Satellite observations (e.g., Xie and Arkin 1997) have revealed that the precipitation over the monsoon ocean regions is

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* School of Ocean and Earth Science and Technology Publication 5887 and International Pacific Research Center Publication 122.

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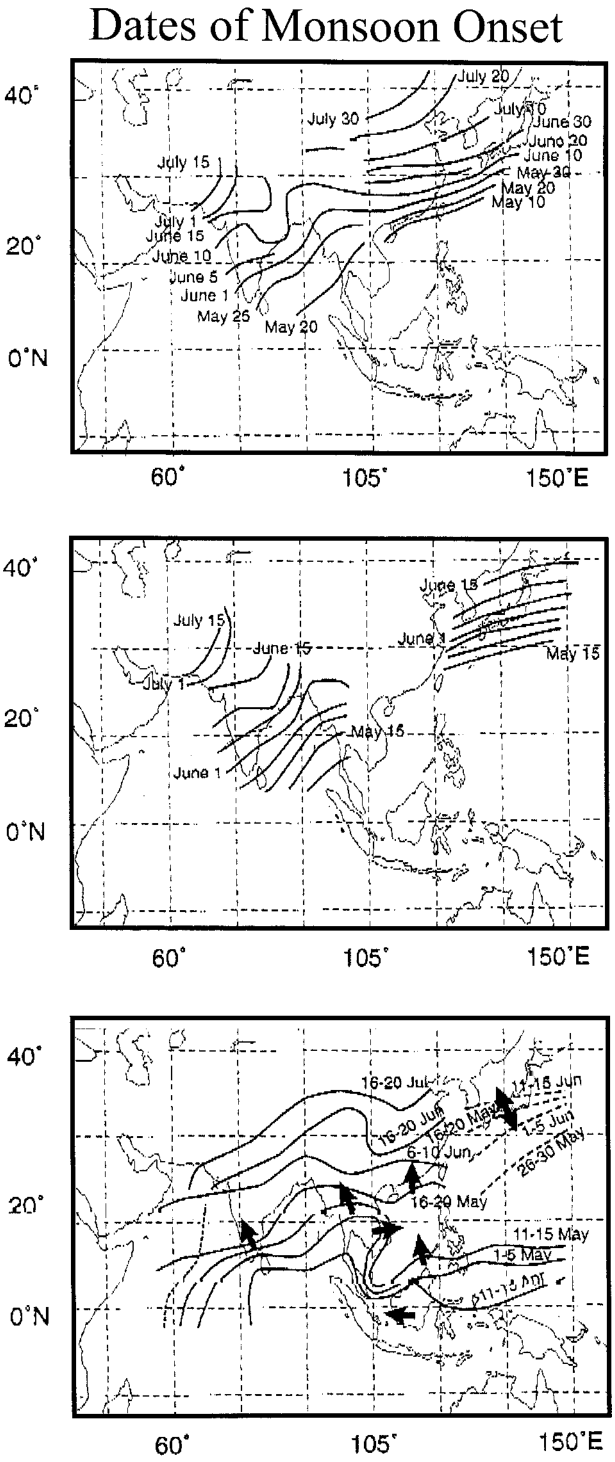

FIG. 1. The onset dates of the summer monsoon as defined by Tao and Chen (1987, upper panel), Tanaka (1992, middle panel), and Lau and Yang (1997, lower panel).

more intense than over the adjacent land areas. From the dynamical and hydrological points of view, it is important to know how the oceanic and continental monsoon rainy seasons are interlinked.

Often overlooked is the tropical western North Pacific (WNP) region (10°–22°N, 120°–170°E), which shows a typical monsoon character (Murakami and Matsumoto 1994). Although the oceanic monsoon over the WNP differs from the continental monsoon in certain aspects, such as the rain-bearing system, both the continental and oceanic monsoons are driven by the annual variation of solar radiation and controlled by the land–ocean thermal contrast. Thus they share common fundamental features, namely, annual reversal of the prevailing winds and the sharp contrast between rainy summer and dry winter. The WNP region has been recognized as a part of the Asian–Pacific monsoon domain both from surface wind criteria (Ramage 1972) and from rainy season characteristics (Wang 1994), yet how the WNP rainy season is related to the other parts of the Asian summer monsoon is not known.

The immense Asian monsoon system, affected by the highest topography on earth, shows regional diversities. Meteorologists in east Asian countries have emphasized the differences between the south Asian and east Asian summer monsoons (e.g., Tao and Chen 1987). In order to identify the differences as well as the linkages between regional monsoon subsystems, we urgently need a universal definition of a monsoon and criteria for the quantitative description of rainfall climatology in the entire Asian–Pacific monsoon domain.

Thus far, the monsoon community has not yet reached a consensus concerning the domain and onset of the Asian–Pacific monsoon. The linkage between the rainy seasons over the Asian continent and those over the adjoining oceans is not well understood. One of the objectives of the present study is to investigate the feasibility of using a concise yet pertinent rainfall parameter and a set of universal criteria to quantify rainy season characteristics for the entire Asian–Pacific monsoon domain. Another purpose is to use the precipitation data derived from satellite observations over the oceans along with rain gauge observations over the continent to build up a unified picture of the spatial and temporal structures of the mean monsoon rainy seasons. Particular attention is given to the contrast and linkage among various regional monsoon subsystems. The results will provide an observational basis for validating and identifying the weaknesses of the existing atmospheric general circulation models and climate system models simulating the Asian–Pacific summer monsoon.

In section 2, we first describe the dataset and the processing procedure. In section 3, an innovative and succinct rainfall parameter is proposed to objectively define the domain and the onset of the rainy season. Section 4 presents the resultant onset, peak, and withdrawal patterns of the Asian–Pacific monsoon rainy season. In section 5, we elaborate on the differences and linkages among the regional components in terms of rainfall climatology. Section 6 discusses issues associated with the analysis and related to understanding the annual cycle of the Asian–Pacific summer monsoon. The last section summarizes our conclusions.

2. Data

The primary datasets analyzed in this study include the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) and the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (Kalnay et al. 1996). The CMAP was derived by merging rain gauge observations, five different satellite estimates, and numerical-model outputs. The climatological pentad (5-day) mean (CPM) rainfall dataset was constructed for the 20-yr period from 1979 to 1998 with global coverage on 2.5° × 2.5° grids. The CPM wind data were derived from daily mean data on 2.5° × 2.5° grids during the same period. Over the ocean, the accuracy and reliability of the pentad mean CMAP on small spatial scales has not been fully determined because of the lack of ground truth observations. Since the CMAP dataset merges multisource estimates, the uncertainties contained in each individual estimate are significantly reduced. A comparative study of CMAP and land-based rain gauge data shows that the two datasets yield similar large-scale pictures over land areas. Thus, it is meaningful to describe large-scale rainfall characteristics using CPM CMAP estimates.

Most previous studies have used a smoothed annual cycle that is defined by the annual mean plus the first four Fourier harmonics of the CPM time series to define the onset of monsoon rainy seasons (e.g., Murakami and Matsumoto 1994; Wang 1994). However, Fig. 2 shows that the onset pentad defined by the smoothed annual cycle often differs considerably from that defined by the CPM series. The discrepancy is particularly large in the regions where the onset is sudden (e.g., Fig. 2a) or the rainy season is short (Fig. 3b). The smoothed annual cycle cannot resolve properly the subseasonal variations such as the well-known double peaks of the rainy season shown in Figs. 3d,e, and 3f. On the other hand, the original CPM time series contains high-frequency fluctuations due to the limited sampling size from which the climate data were derived. A decision has to be made as to how many harmonics should be used to retain both the seasonal and subseasonal signals. Sensitivity tests of the results to Fourier truncation indicate that the sum of the first 12 harmonics (period longer than 1 month) is best suited for our purpose. A parallel analysis was carried out using the time series retaining the first 18 harmonics (period longer than 4 pentads); the resultant differences are insignificant as far as the large-scale features are concerned. As shown in Figs. 2 and 3, the time series including the first 12 harmonics captures both the seasonal and subseasonal signals and depicts very well the time at which the local rainfall rate reaches peak or exceeds (drops below) 6 mm day^{-1}. In the following analysis of rainfall, we will use the *reconstructed* pentad series, which consists of the long-term mean and the first 12 harmonics, to define the onset, peak, and withdrawal of the monsoon rainy season.

The reconstructed time series consists of a smoothed annual cycle and a climatological intraseasonal oscillation (CISO). The CISO component is included because it represents subseasonal variation, an intrinsic component of the monsoon climate (LinHo and Wang 2002, manuscript submitted to *J. Climate*, hereafter LW), Wang and Xu (1997) have shown the statistical significance of the CISO in the boreal summer monsoon domain by using a sign test, an extreme test (Monte Carlo simulations), and an amplitude test (the *t* test).

3. Definition of the monsoon rainy season

It has been generally recognized that a typical monsoon rainy season implies significant annual variation, an intense rainfall rate, and concentration of yearly rainfall in the local summer. Quantitative description of these characteristics requires perhaps three parameters: 1) the total amount of summer rainfall that measures the intensity of the rainy season (Fig. 4a), 2) the annual range of rainfall rate that measures the amplitude of annual variation (Fig. 4b), and 3) the seasonal distribution of rainfall that measures the ratio of summer to yearly rainfall (Fig. 4c).

Figure 4a shows total summer (May–September) precipitation. The summer precipitation in semiarid and arid continental Asia is below 300 mm (equivalent to a summer mean rainfall rate of 2 mm day^{-1}), and a rainy season cannot be clearly defined because of the absence of an intense rainy period. Figure 4b shows the annual range. The largest annual range exceeding 17 mm day^{-1} is found over the sea in the following areas: the central Bay of Bengal, the southeastern Arabian Sea, the Philippine Sea, and the South China Sea (SCS). These regions of largest annual range tend to coincide with the regions of maximum summer rainfall (Figs. 4a and 4b). Figure 4c shows the ratio of summer to annual rainfall that reflects the seasonal distribution of precipitation. A large ratio implies a heavy summer rainy season versus a dry winter. Over the Indian monsoon region and northeast continental Asia, the ratio exceeds 85%. Over the Philippine Sea, the ratio is also relatively high (over 60%). The level of 55% provides a reasonable demarcation for the equatorial perennial and monsoon rainy seasons.

Note that the areas where the annual range falls below 5 mm day^{-1} coincide well with the arid and semiarid continental regions (Figs. 4a and 4b). Thus, the annual range can not only measure the amplitude of annual variation, but also effectively distinguishes the semiarid continental regime from the monsoon regime. We note also that both the equatorial perennial rain regime and the North Pacific oceanic regime have a moderate contrast between summer and winter. Thus, to further distinguish the monsoon regime from the perennial and

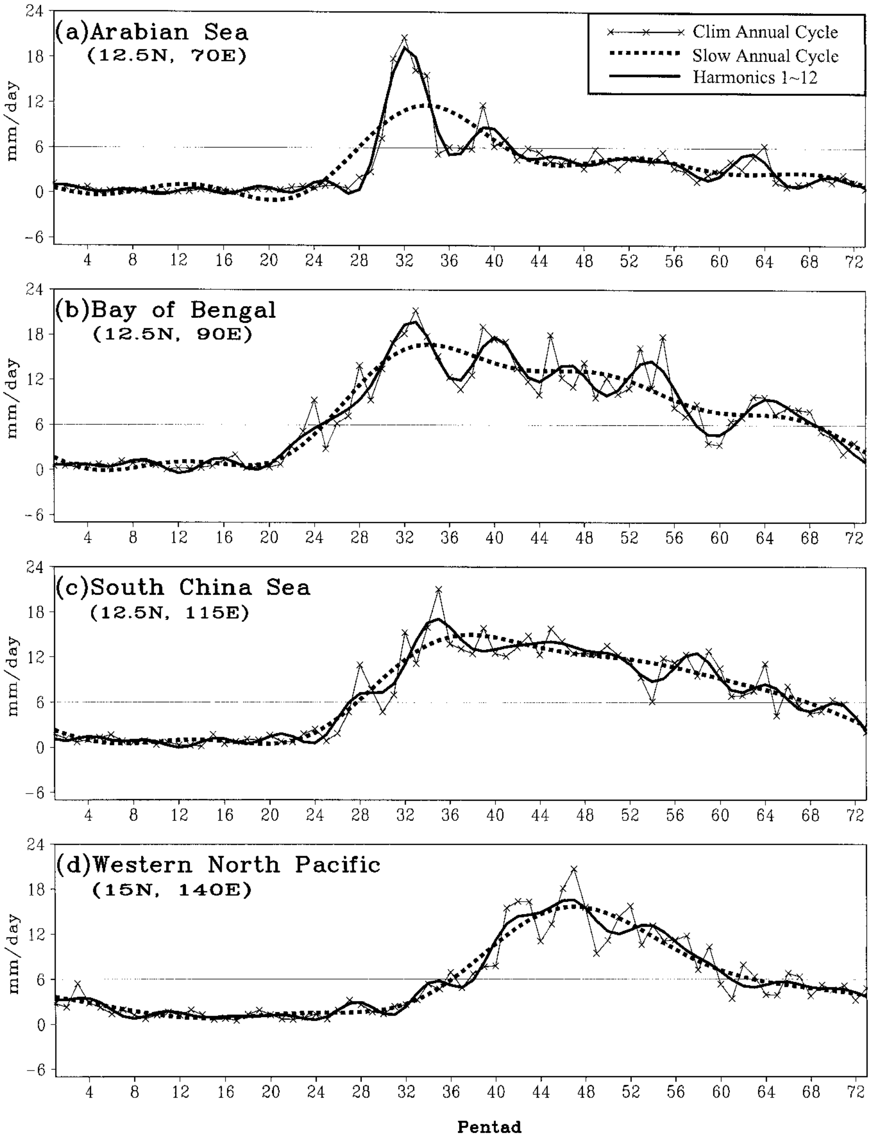

FIG. 2. CPM precipitation rate (mm day^{-1}) (thin solid with cross mark) observed at (a) 12.5°N, 70°E, (b) 12.5°N, 90°E, (c) 12.5°N, 115°E, and (d) 15°N, 140°E. The locations of these four representative points are marked by crosses in Fig. 4. The dotted line denotes the slow annual cycle, obtained by the summation of the mean and the first four Fourier harmonics. The thick line represents the summation of the mean and the first 12 Fourier harmonics. The CPM climatology is derived from CMAP data (Xie and Arkin 1997) for the period 1979–97.

oceanic regimes, we design a compound rainfall variable that is able to synthesize the aforementioned three characteristics. This variable is defined by the difference between the pentad mean (R_i) and the January mean (R_{JAN}) precipitation rates:

$$\mathrm{RR}_i = R_i - R_{\mathrm{JAN}}, \qquad i = 1, 2, \ldots, 73. \tag{1}$$

The quantity, RR_i, is referred to as the *relative pentad mean rainfall rate.* In the Northern Hemisphere, January mean rainfall represents the winter mean precipitation rate. Thus the RR_i essentially measures the contrast of the rainfall rates between a specific pentad and the corresponding winter.

For a typical Northern Hemisphere summer monsoon rainy season, one expects that the maximum value of RR_i, that is, Max (RR_i; hereafter the *monsoon range*), must be sufficiently large and occur in summer (May–September). To quantify "sufficiently large," we present in Fig. 5 the geographic distribution of the monsoon range. The cutoff value of 5 mm day^{-1} appears to represent a sufficient strength for the rainy season. Hence this criterion effectively separates the dry continental

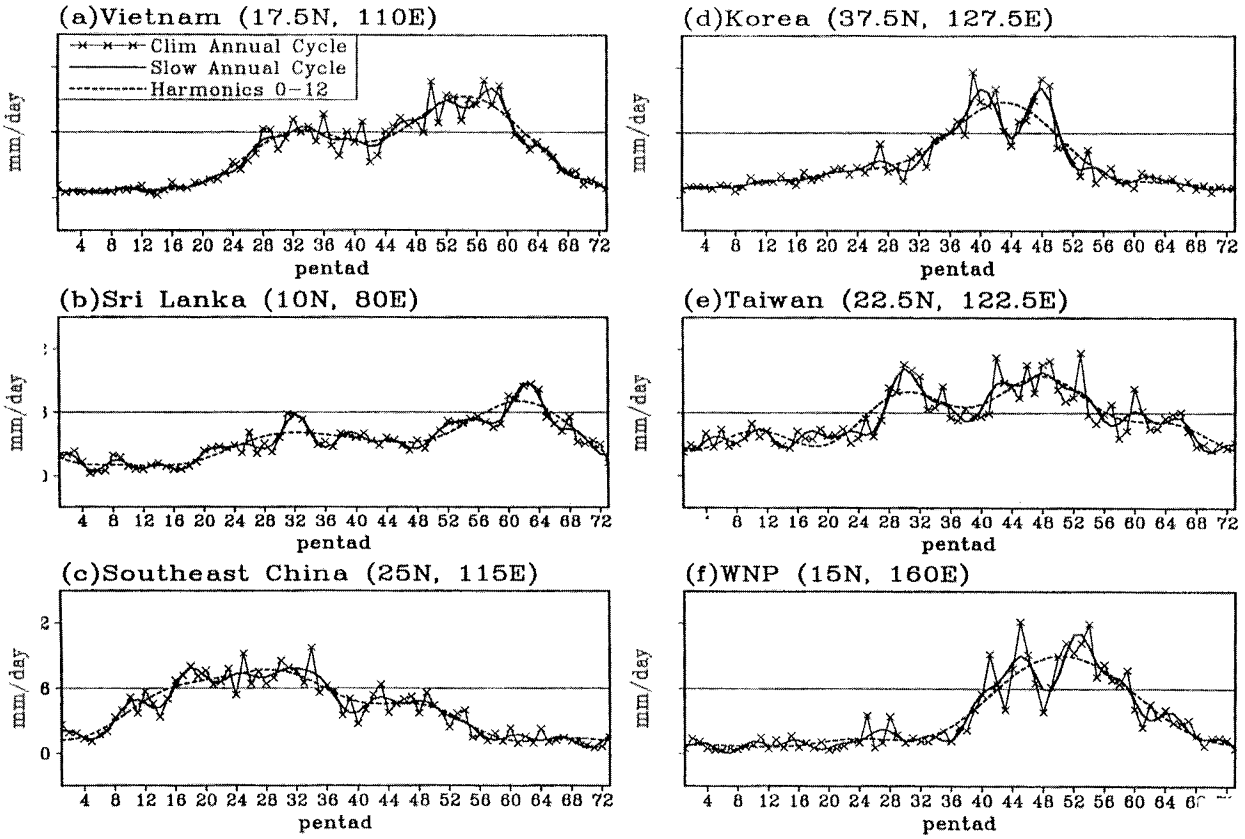

FIG. 3. The same as in Fig. 2 except for the following locations: (a) Vietnam coast (17.5°N, 110°E); (b) north of Sri Lanka (10°N, 80°E); (c) southeast China (25°N, 115°E), (d) Korea (37.5°N, 127.5°E), (e) Taiwan (22.5°N, 122.5°E), and (f) WNP (15°N, 160°E). The exact locations of these points are marked as triangle dots in Fig. 4.

climate from the monsoon climate (see Figs. 4a and 4b). Near the equator where the January rainfall rate is relatively high (higher than 5 mm day^{-1} for instance), the above criterion may not sufficiently reflect a significant winter–summer contrast. This situation is found in the equatorial regions of the western Pacific and the eastern Indian Ocean. In this situation, it is more appropriate to require the monsoon range to exceed the *local* January mean rainfall rate. This supplementary criterion can effectively exclude the equatorial perennial rainy regime.

The domain of the summer monsoon rainy season is defined as the regions where the monsoon range, Max (RR_i), exceeds 5 mm day^{-1} (and the local January mean rainfall rate) and occurs in boreal summer (May–September). The domain defined in this way (the thick solid curve in Fig. 5) agrees well with those delineated using the three parameters shown in Fig. 4, suggesting that the relative pentad mean precipitation rate is indeed a succinct and effective parameter that defines the domain of the monsoon rainy season.

The relative CPM rainfall rate can also be used to conveniently define the onset, peak, and withdrawal of the rainy season. Previous studies have often adopted a uniform criterion to define the onset, for instance, a CPM rainfall rate exceeding 6 mm day^{-1} (Lau and Yang 1997) or CPM outgoing longwave radiation below 230 W m^{-2} (Murakami and Matsumoto 1994). Such a uniform criterion is perhaps suitable for the tropical monsoon regions but is not applicable in a domain with a large latitudinal extent, such as east Asia, because the strength of the rainy season varies considerably with latitude. Use of the relative CPM rainfall rate, however, can circumvent this problem. Since the January mean rainfall rate varies with geographic location, a constant criterion for the relative CPM rainfall rate actually implies a variable threshold for the original CPM rainfall rate.

The Julian pentad in which the relative CPM rainfall rate [RR_i defined by Eq. (1)] exceeds 5 mm day^{-1} is defined as the onset pentad. Similarly, the transitional pentad in which the relative CPM rainfall rate drops below 5 mm day^{-1} is defined as the withdrawal pentad.

4. The onset, peak, and withdrawal patterns

The rainy season starts from the Asian marginal seas (Fig. 6). The earliest onset of rainy season is found in late April (P23–P24) over a *limited* area in the southeast Bay of Bengal around (8°N, 95°E). This earliest onset

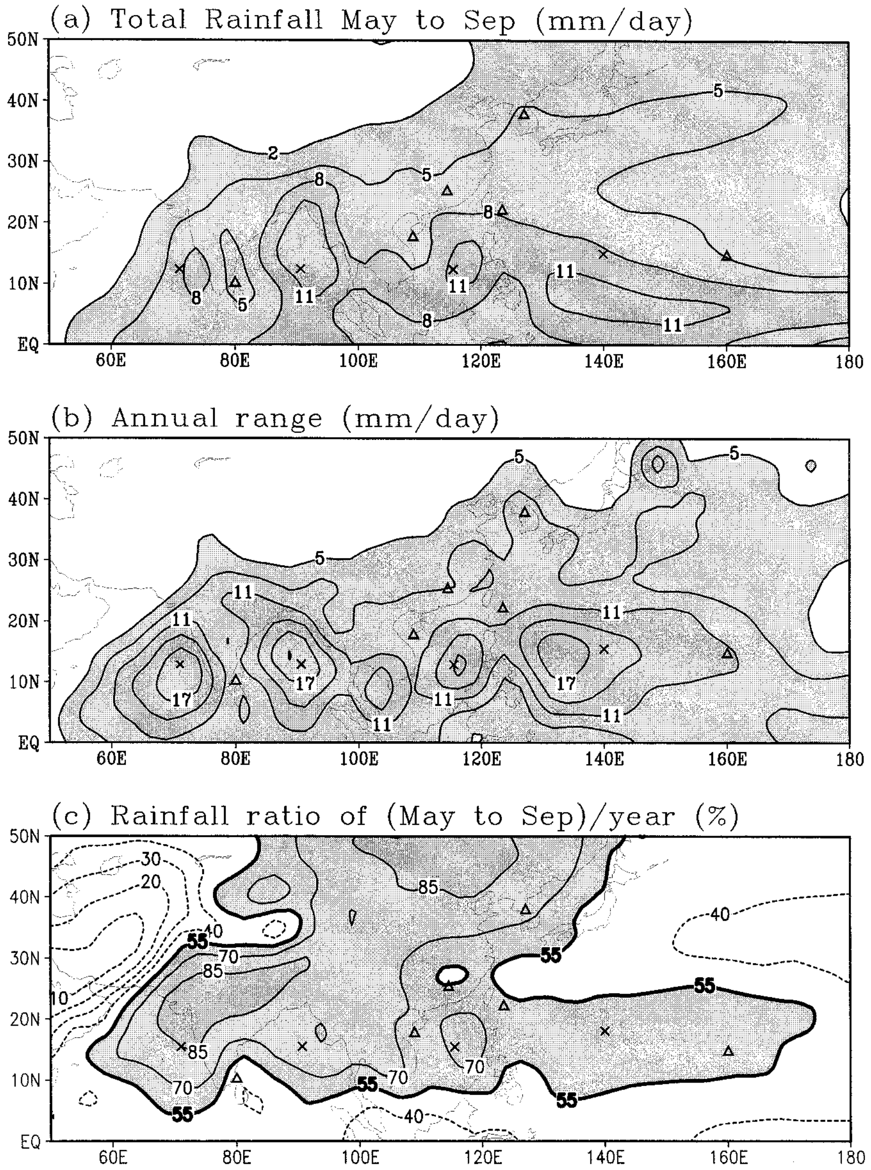

FIG. 4. (a) Total summer (May–Sep) precipitation rate (mm day^{-1}), (b) annual range (the max minus min) of the CPM precipitation rate, and (c) the ratio of summer to annual precipitation. The climatological rainfall time series of points marked with a cross were shown in Fig. 2. The triangle-marked points denote areas with nonmonsoon or peculiar rainfall character with their rainfall time series given in Fig. 3.

of rainy season results from a rapid northward march of the convection center from west of Sumatra to the Andaman Sea along the land bridge between Indonesia and Indochina. Accompanying this earliest onset, monsoon westerlies burst along and to the north of the equatorial Indian Ocean (figure not shown). Thereafter, the onset extends northeastward rapidly, passing over the Indochina Peninsula in early May (P25–P26) [in agreement with Matsumoto (1997) and Zhang et al. (2002, manuscript submitted to *J. Climate*)], over the South China Sea (SCS) in mid-May (P27–P28), and into the subtropical WNP by P29, starting the pre–mei-yu season over Taiwan, China, and Okinawa, Japan, (Tanaka 1992; Chen 1994). Right after the SCS onset, a planetary-scale rainband is established, extending from the south Asian marginal seas all the way to the south of Japan (25°N, 150°E). This rainband bridges the tropical south Asian monsoon and subtropical east Asian monsoon. Thus, the SCS monsoon onset signifies the large-scale onset of the Asian summer monsoon.

The onset of the monsoon rainy season occurs progressively later northwestward from the monsoon oceans toward inland areas (Fig. 6). Over the Arabian Sea, the monsoon rain migrates northward rapidly,

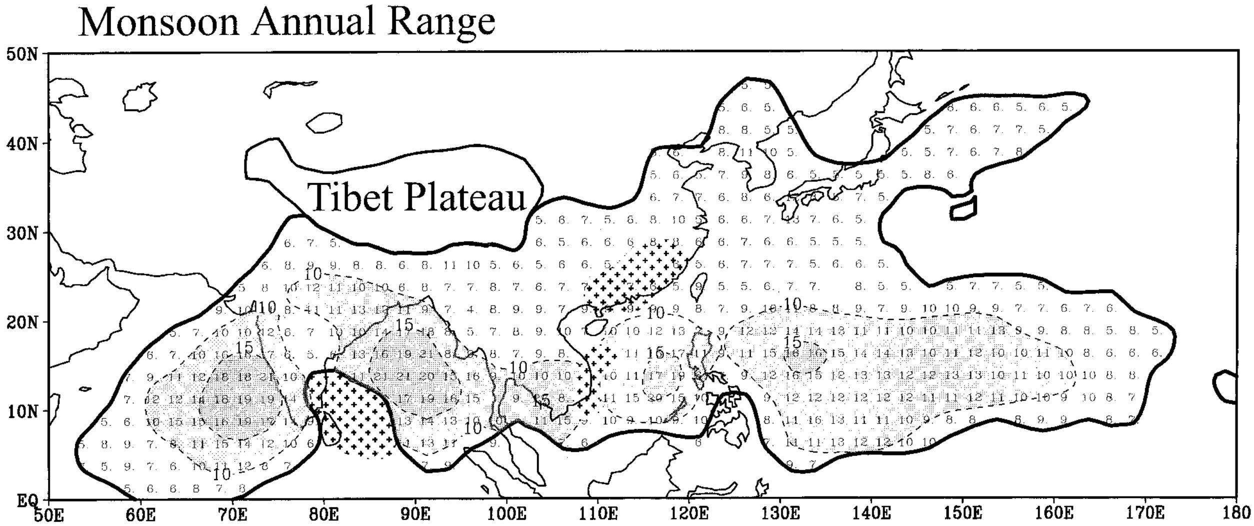

FIG. 5. The monsoon annual range defined by the annual maximum CPM minus the Jan mean rainfall rate (in units of mm day^{-1}). The thick solid lines represent the Asian–Pacific summer monsoon domain defined by the monsoon annual range. See text for detailed definition. The Tibetan Plateau is outlined by the 3000-m contour. Values of the monsoon annual range are given for each 5° lat by 5° long point, with the high-value areas concentrated in three bays and the WNP region. The patches with crosses show nontypical monsoon rainfall pattern. Shading is at intervals of 5 mm day^{-1}.

reaching the southern tip of the Indian subcontinent by P30 (26–30 May) then 20°N by P32 (5–9 June). Using rain gauge data, Joseph (1994) shows that the rainy season in Kerala, the southern tip of India, begins around 1 June. We note that this northward progression of onset has been missing from previous analyses (Fig. 1). Over the Bay of Bengal, the onset marches slowly northwestward, reaching the northeast coast of India in early June (P32–P33). The onset pentads along this northwestward route show a good agreement with the pattern presented in Fig. 1a, which was derived based on rain gauge observations (Rao 1976). Over east Asia, the monsoon rainband reaches the Yangtze River (Changjiang) valley and southern Japan by 5–14 June (P32–33),[1] starting the Chinese mei-yu and Japanese baiu season. By late June and early July, the monsoon rainband moves farther north, and the Korean Changma (rainy season, see Ho and Kang 1988) starts.

In early June, the synchronized onset of the Indian rainy season and the mei-yu/baiu forms a grand onset pattern, which concurs with the early June reversal of the upper-tropospheric meridional temperature gradients in south Asia. This grand onset pattern signifies the second stage of the Asian summer monsoon onset (He et al. 1987; Yanai et al. 1992). The advance of the monsoon rainband from monsoon oceans to the Asian continent characterizes the transition from the first to the second stage of the Asian summer monsoon onset.

In contrast to the continuing northwestward and northward progression of the rainy season in south and east Asia, the rainy season over the WNP displays a stepwise, multiple-phase onset that takes place in mid-June (P33–P34) over the southwestern Philippine Sea, in mid-July (P39–P41) in the core region of the WNP monsoon domain, and around 8–13 August (P44) in the northeast portion of the WNP monsoon domain. This stepwise onset is closely related to the CISO and monsoon singularities over the WNP. Wang and Xu (1997) documented four CISO cycles in the northern summer monsoon domain. The wet phases of the first three CISO cycles occur, respectively, around P28, P34, and P45, which correspond to the onset of the SCS monsoon, the onset of mei-yu/baiu, and the peak of the western North Pacific summer monsoon (WNPSM; also see Kang et al. 1999). The stepwise onset has been speculated to result from seasonal phase locking of the intraseasonal oscillation that interacts with the underlying ocean (Ueda et al. 1995; Wu and Wang 2000a,b).

The peak rainy season happens primarily during *four specific periods* (Fig. 7). The earliest peak occurs from 26 May to 9 June (P30–P32) over the southern Arabian Sea, the southeast Bay of Bengal, and in the subtropical front zone extending from the southeast coast of China via Okinawa to the south of Japan (30°N, 145°E). The second peak takes place in late June (P35–P36) in the mei-yu/baiu region and in the central SCS and southwestern Philippine Sea. The third phase occurs in the second half of July (P40–P42) over India and northeastern continental Asia, including the lower reaches of the Yellow River valley, the Yellow Sea, Korea, and northeast China. The fourth phase from 5 to 19 August (P44–P46) marks the height of the rainy season in the WNP, roughly between 15° and 25°N and from 115° to

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[1] There are 73 pentads (5-day periods) in a 365 day year. P32 refers to the 32d pentad after the start of the year.

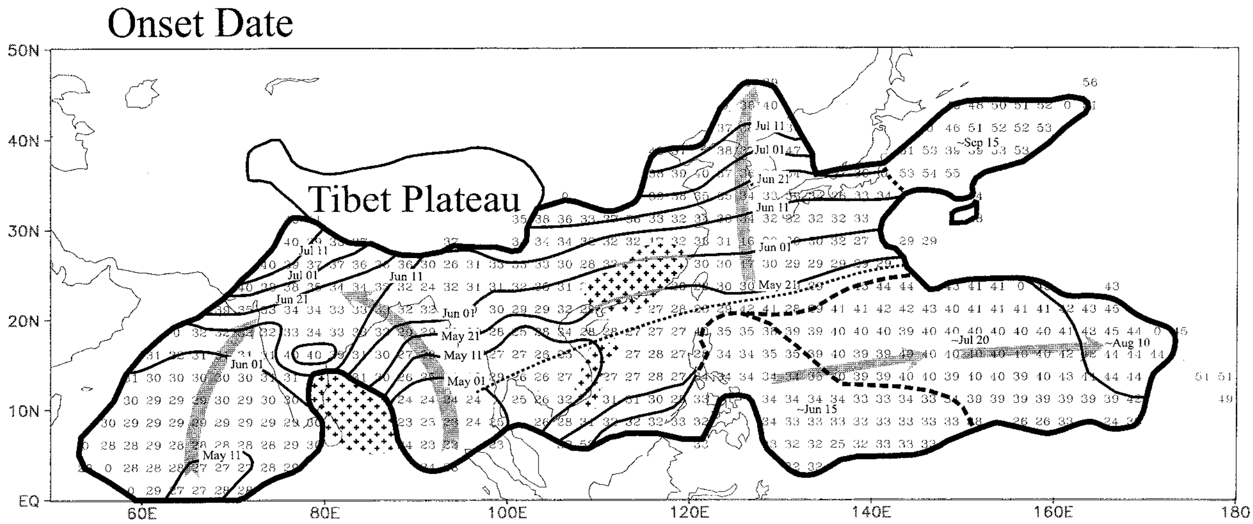

FIG. 6. Dates of onset determined by relative CPM rainfall. The onset pentad is the first pentad of the rainy season. The data used and the way in which the monsoon domain and the Tibetan Plateau are denoted are the same as in Fig. 5. The thick dashed lines denote discontinuities (merger of three or more contours). The arrows point to the directions of rain-belt propagation. The thin dashed line divides subtropical monsoon and oceanic monsoon regions, their onset patterns are entirely different.

170°E. The occurrence of the peak rainy season described here is consistent with the July–August shift of the convection centers from Indian monsoon to WNP monsoon region as emphasized by LW. In addition, over the southeast corner of the WNP and the northeast of Japan the rainy season (Shurin or autumn rain) peaks in mid- to late September (P52–P55).

Figure 8 shows the large-scale withdrawal pattern. The rainy season over the central Arabian Sea withdraws extremely early because it is determined by the same onset rain surge. This early termination is in part due to the rapid cooling of the western-central Arabian Sea after the outburst of the Somali jet. The retreat of the monsoon rainy season in east Asia shows a northward progression similar to the onset pattern. This seemingly odd feature is due to the fact that both the onset and withdrawal of the east Asian monsoon rainy season result from the northward migration of the monsoon front and the western Pacific subtropical high (WPSH). Thus the rainy season over east Asia is generally shorter than 8 pentads except in the vicinity of South Korea, where the retreat, in conjunction with tropical storm activity,

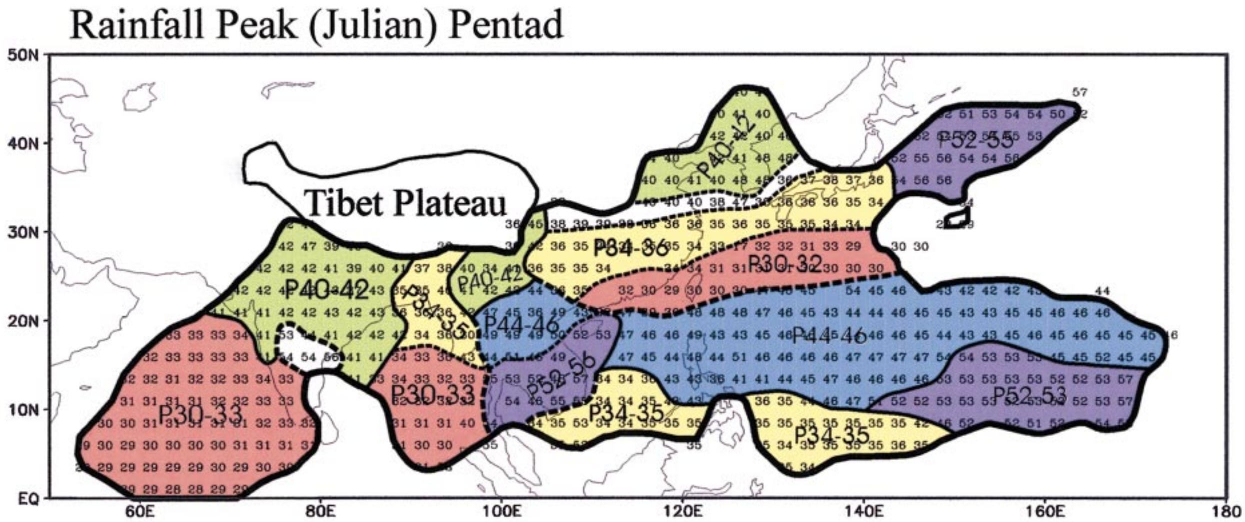

FIG. 7. The same as in Fig. 6 except for the timing of monsoon rainfall peak: the Julian pentad during which the annual maximum rainfall occurs. The thick dotted lines indicate strong discontinuities. The rainfall peak pentads can be divided into four periods in the boreal summer, colored by light red(30 ~ 33), yellow(p34 ~ 36), green(40 ~ 42), blue(p44 ~ 46), and one period in boreal autumn, purple(p52 ~ 56).

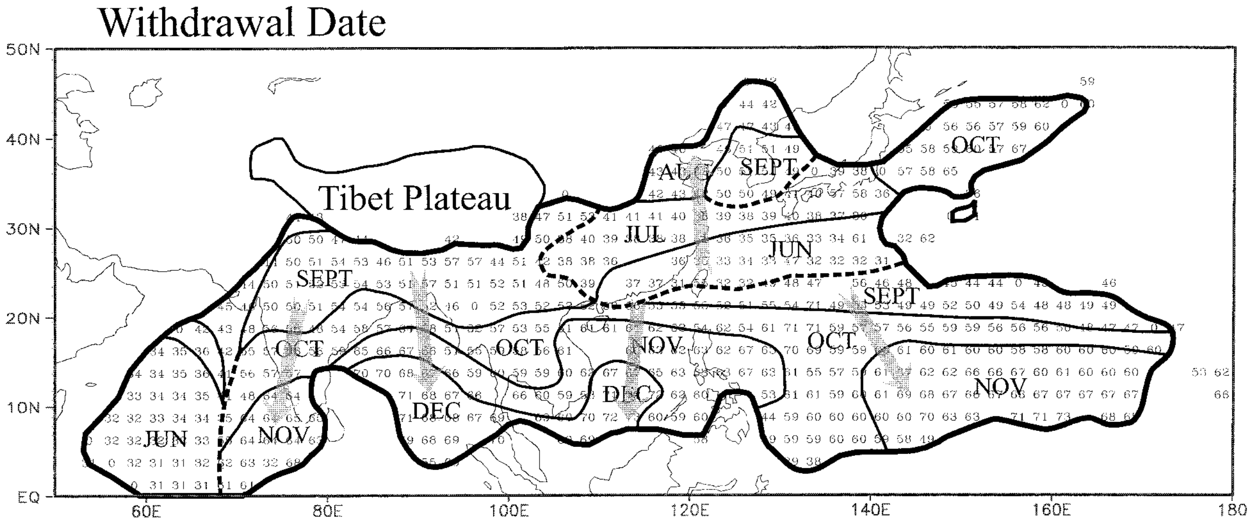

FIG. 8. The same as in Fig. 6 except for the withdrawal date of the rainy season. The withdrawal pentad is the last pentad of the rainy season. The arrows also indicate where the rain belts migrate. Note that in the east Asian summer monsoon (EASM) the rain belt, similar to the onset pattern, also retreats from south to north whereas in the Indian summer monsoon (ISM) the withdrawal route just takes opposite direction.

produces a second rainy peak in August (Fig. 3d). This causes the rainy season to last longer (about 15 pentads). In sharp contrast, over the tropical monsoon regions, the rainy season retreats progressively southward. Thus the length of the rainy season generally increases toward the equator. The longest rainy season is found in the southeast Bay of Bengal; it lasts about 7 months.

5. The regionality and linkage of the Asian–Pacific monsoon system

The rainy season characteristics described in the previous section suggest demarcation of the Asian–Pacific monsoon into three components: the Indian summer monsoon (ISM), the WNPSM, and the east Asian summer monsoon (EASM) (Fig. 9). The ISM and WNPSM are tropical monsoons in which the low-level winds reverse from winter easterlies to summer westerlies (Fig. 10). The EASM is a subtropical monsoon in which the low-level winds reverse primarily from winter northerlies to summer southerlies. The EASM domain defined here agrees with the conventional notion, which includes the region of 20°–45°N and 110°–140°E, covering eastern China, Korea, Japan, and the adjacent marginal seas.

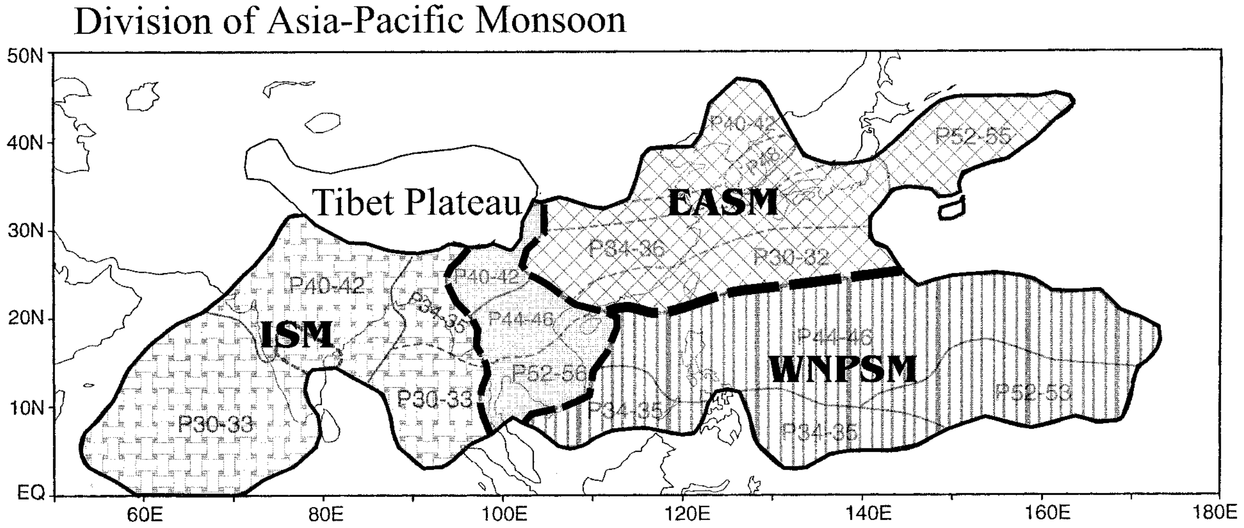

FIG. 9. This map divides the Asian–Pacific monsoon into three subregions. The ISM and western WNPSM are tropical monsoon regions. A broad corridor in the Indochina Peninsula separate them. The subtropical monsoon region is identified as the EASM. It shares a narrow borderline with the WNPSM.

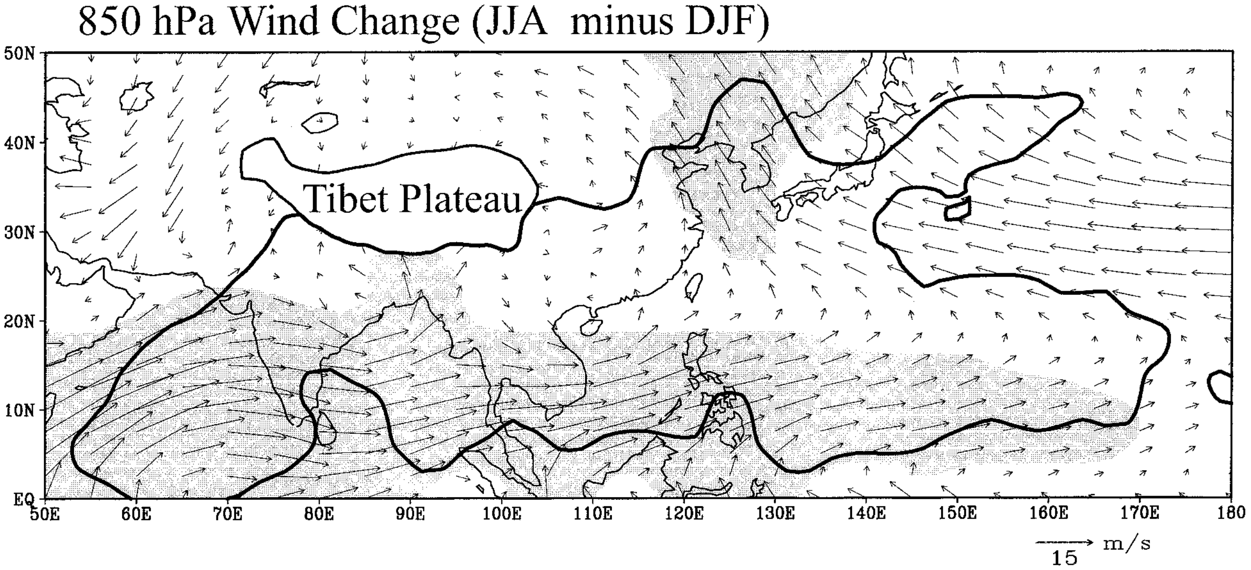

FIG. 10. Summer (Jun, Jul, Aug) minus winter (Dec, Jan, and Feb) 850-hPa winds (vector). The arrow shown in the lower-right corner gives wind scale. The shading indicates regions where the differential wind speed, either a northward component or a eastward component, exceeds 4.5 m s^{-1}.

The EASM and WNPSM are separated by a remarkable discontinuity in the rainy season onset, peak, and withdrawal patterns along the southern flank of the WPSH extending from Hainan Island (21°N, 110°E) to (25°N, 145°E) (Figs. 6, 7, and 8). The EASM retreats progressively *poleward* from June to early September while the WNPSM withdraws *equatorward* after mid-September (Fig. 8).

In between the ISM and WNPSM is a broad transitional zone over Indochina and the Yun-Gui Plateau (a southeastward extension of the Tibetan Plateau). Over Indochina, the rainy season reaches its maximum intensity in autumn (e.g., Fig. 3a) and has double peaks occurring in September–October and May, respectively (Matsumoto 1992), a characteristic that differs substantially from the rainy seasons in the adjacent ISM and WNPSM (Fig. 7). This discontinuity provides a broad ‘‘buffer’’ zone between the ISM and WNPSM. Major differences between the ISM and WNPSM are summarized as follows. First, the rainy season reaches its height in June–July in the ISM, and in August–September in the WNPSM (Fig. 7). This difference reflects a large-scale shift of the maximum convection and diabatic heat source from the ISM region in early summer to the WNPSM region in August–September (LW). Second, their onset patterns are remarkably different (Fig. 6). In the ISM, a northward march of the rain belt over the Arabian Sea and a northwestward migration over the Bay of Bengal, converging on the Indian subcontinent, dominate the picture. In contrast, the WNP onset is a *three-phase* process that is, by and large, controlled by the CISO.

The pronounced regional differences are primarily attributed to the locations of the subsystems relative to the land–ocean configuration and the thermal and dynamical effects of the Tibetan Plateau. Over India, the *meridional* land–sea thermal contrast and the effects of the elevated Tibetan Plateau heat source reinforce the interhemispheric thermal contrast derived from differential solar radiation, resulting in an extremely energetic southwesterly monsoon. The EASM region is dominated by an east–west, land–sea thermal contrast, which tends to induce a zonal pressure gradient between the Asian continental low and the oceanic WPSH. Thus the monsoon is characterized by an annual reversal of the meridional wind component. In conjunction with the influence of the north–south differential solar forcing and the east–west, land–ocean thermal contrast, the WNP monsoon trough directly controls summer rainfall in a vast oceanic region of the WNP (7°–20°N, 110°–170°E).

Although there are clear distinctions in the characteristics of rainy season and low-level wind variation among India, east Asia, and the WNP, the three components are no doubt interlinked. Tao and Chen (1987) view the east Asian and WNP monsoons as constituting an integrated system. This notion is supported as far as the interannual variation of the summer monsoon is concerned (Nitta 1987; Huang and Lu 1989; Wang et al. 2001). The seasonal variation analyzed here reveals a coupling between the east Asian and WNP monsoon in June and July as manifested by two sudden changes. In mid-June (P33–P34), the monsoon rains burst simultaneously in the vicinity of the Philippines and along the mei-yu/baiu front, and in late July (P40–P42) when the monsoon rain starts in the WNP, the rainy season in northern China reaches its height. The aforementioned linkage is established through the movement of the WPSH. Note, however, the coupling through the WPSH tends to collapse after the WNP monsoon gyre forms in late July and early August. In August and September, the east Asian monsoon is linked to the active-break cycle of the WNP monsoon primarily through tropical cyclone activity, especially that of the northward recurving tropical cyclones affecting coastal regions of east Asia. The peaks of the second rainy season, occurring in Korea and Taiwan (Figs. 3d and 3e), are examples of influence from tropical storms. In the same period, the intraseasonal convective anomalies propagate westward from 170°E into the Bay of Bengal, providing a linkage between the Indian and WNP monsoons (Wang and Xu 1997). The onset patterns in the ISM and EASM exhibit an evident similarity (Fig. 6). Although being separated by the Yun-Gui Plateau, the Indian monsoon rain surges enhance the rainfall of the east Asian monsoon via strengthening northeastward transport of moisture above the terrain. The interaction between the three regional components deserves further investigation.

6. Discussion

a. Definition of a monsoon

The original definition of a monsoon was solely based on the annual reversal of surface winds (Ramage 1972). However, the meteorological significance and practical importance of rainfall makes it desirable to define monsoons in terms of rainfall characteristics. In this paper we have explored the possibility of defining a monsoon domain using rainy season characteristics. The domain of the monsoon rainy season defined by rainfall characteristics (Fig. 5) is dynamically consistent, in terms of large-scale features, with the region where the 850-hPa winds exhibit significant seasonal reversal from winter easterlies (northerlies) to summer westerlies (southerlies) (Fig. 10). From winter to summer, a giant circumcontinental cyclonic circulation forms as a result of the increase in the thermal contrast between the land and ocean. A belt of prominent westerlies is found between 5° and 20°N and from the Arabian Sea (40°E) to the eastern Philippine Sea (160°E; the southwest summer monsoon). These westerlies tend to be located to the southwest of the monsoon rainy region and can be understood as a result of the interaction between the convective heat source and the corresponding Rossby wave response (Gill 1980). Significant southerlies are found between 110° and 140°E in east Asia north of 22°N (the southeast summer monsoon). As seen from Figs. 6 to 8, the rainfall characteristics also change remarkably around 22°N.

Our definition of the rainy season does not consider the types of rain-bearing systems. One might argue that the rains produced by tropical cyclones are not monsoon rains. However, the tropical cyclone, like other synoptic systems embedded in the planetary-scale monsoon circulation (such as monsoon depressions and the mesoscale cyclones in the mei-yu front) is just one of the rain-bearing systems. Over the Bay of Bengal, tropical cyclones furnish a significant portion of the monsoon rainfall. In east Asia, the second peak of the rainy season occurring on the Indochina peninsula, Taiwan, and South Korea (Figs. 3a, 3d, and 3e) is primarily attributed to tropical cyclone–related rainfall. Therefore, in our definition, we focus only on rainfall intensity, continuity, annual range, and seasonal distribution, but not on the nature of rain-bearing systems.

b. Atypical monsoon rainy seasons

A skewed seasonal distribution is found over the Arabian Sea and Bay of Bengal, where rainfall shows a sharp increase in late May, a peak in early June, and a slow decrease thereafter (Fig. 2a,b). Over the Arabian Sea, both the *peak* and *onset* of the rainy season occur progressively northward (Figs. 6 and 7). The phase speed of the northward propagation is about 1° of latitude per day, which approximately equals that of the transient intraseasonal oscillation (ISO) in that region. This suggests that the mean monsoon onset/peak over the Arabian Sea results from a ‘‘punctuated’’ occurrence of the northward-propagating intraseasonal oscillations. This tight phase lock of ISO to the annual cycle is attributed to the modulation of ISO by the large-scale circulation that is driven by the punctuated annual warming of the Indian subcontinent and northern Indian Ocean.

A bimodal seasonal distribution with maximum rainfall occurring in October–November and a secondary maximum occurring in June is found over Sri Lanka and Indochina (Figs. 3a,b). In southeast India, Sri Lanka, and the southwestern Bay of Bengal is a region called the rain-shadow area of the Indian monsoon. The summer rainfall there is substantially lower than other regions of the Indian peninsula (Annamalai et al. 1999).

The ‘‘spring rain’’ over southeast China signifies the beginning of the local rainy season (Fig. 3c). Traditionally, the spring rain has not been considered to be a part of the summer monsoon rainy season, because the large-scale circulation and rain-bearing systems differ from those associated with the mei-yu. In these regions, however, mid-summer (July–August) dryness is a climatological feature (Fig. 3c; Ding 1992); thus, the spring rain represents a major rainy season during the course of the year.

c. Simulation of the rainy season's characteristics

The annual migration of the convection centers has been considered as resulting from the differential response of land and ocean to the annual cycle of solar forcing (Webster 1987). The annual march of sea surface temperature (SST) may also play an important role (Shukla and Fennessy 1994; Wang 1994; Murakami and Matsumoto 1994; Ueda et al. 1995; Wu and Wang 2000a,b). On the other hand, the monsoons have strong feedback to the annual cycles of warm pool SST and land surface conditions. Thus, the complex behavior of the monsoon rainy seasons has to be understood through coupled atmosphere–ocean–land models.

Current climate models have notable deficiencies in simulating the south Asian summer monsoon (Sperber and Palmer 1996; Sperber et al. 2001). The performance of climate models in simulating the east Asian and WNP monsoons is even poorer than the simulation of the ISM (Kang et al. 2001). Many general circulation models (GCMs) severely underestimate the rainfall intensity and seasonal variability of the WNP summer monsoon. Most of the models also fail to reproduce the east Asian mei-yu/baiu front. Present model intercomparison has been focused on south Asian monsoon simulation with less attention paid to the WNPSM, a region perhaps crucial for the global climate system. The results derived from the present analysis suggest that the continental and oceanic monsoons consist of integrated monsoon hydrological cycles. The simple yet objective definitions of monsoon domain, onset, peak, and withdrawal provide a useful validation tool for diagnosis of the GCMs.

7. Conclusions

An adequate description of the spatial–temporal structure of the mean Asian–Pacific monsoon rainy season should take the intrinsic subseasonal components into account. This study shows that the domain, onset, peak, and withdrawal of the rainy season can be quantitatively described by using a single rainfall variable with a suite of universal objective criteria. This variable is called relative pentad mean (the pentad mean minus the January mean) precipitation rate. The monsoon domain and rainy season delineated by the relative pentad mean rainfall rate exceeding 5 mm day^{-1} reflect the essential features of monsoon climate: a significant summer–winter rainfall contrast and an intense concentration of rainfall in the summer.

The large-scale onset of the Asian summer monsoon begins with the rainfall surges over the South China Sea (SCS) in mid-May, which establishes a planetary-scale *monsoon rainband* extending from the south Asian marginal seas (the Arabian Sea, the Bay of Bengal, and the SCS) to subtropical western North Pacific (WNP). The onset then gradually progresses northward and northwestward from the Asian marginal seas and the subtropical WNP toward inland areas. The synchronized onset of the Indian rainy season and the mei-yu/Baui in early June forms the second phase of the Asian monsoon onset. The peak rainy seasons tend to occur in stepwise phases, respectively, in *early June* over the central Arabian Sea, southeast of Bay of Bengal, and the subtropical WNP; in *late June* over the mei-yu/baiu region and the vicinity of the southern Philippines; in *late July* over India and northern China; and in *mid-August* over the tropical WNP (10°–22°N, 120°–160°E). The rainy season retreats progressively northward in east Asia during July and August, while southward in the ISM and the WNPSM after mid-September. The geographic distributions of the onset, retreat, and peak of the rainfall annual cycle exhibit remarkable regionality among the three monsoon subsystems—the ISM, WNPSM, and EASM. However, they are also closely interlinked as discuused in section 5.

The span of CMAP data is only 20 yr, which falls short for a reliable description of climatological features. Given the weaknesses of all the available rainfall datasets, information about oceanic regions derived from the current analysis should be viewed as preliminary and should be updated whenever longer-term and more accurate data become available.

Acknowledgments. The authors thank Ms. Zhen Fan for making numerous draft plots; Dr. R. Wu, Prof. S. Businger, and Mr. Chi-Bao Fu for their assistance in making the final figures; and Drs. Kemball-Cook and Annamalai for their comments. This work is supported by grants from the NOAA Office of Global Change and the ONR Marine Meteorology Program (N00014-96-1-0796). Prof. LinHo is supported by NSC 89-2111-M-002-006-AP7. The International Pacific Research Center is sponsored in part by the Frontier Research System for Global Change.

REFERENCES

Annamalai, H., J. M. Slingo, K. R. Sperber, and K. Hodges, 1999: The mean evolution and variability of the Asian summer monsoon: Comparison of ECMWF and NCEP–NCAR reanalyses. *Mon. Wea. Rev.,* **127,** 1157–1186.

Chen, G. T.-J., 1994: Large-scale circulations associated with the East Asian summer monsoon and the Mei-Yu over south China and Taiwan. *J. Meteor. Soc. Japan,* **72,** 959–983.

Ding, Y.-H., 1992: Summer monsoon rainfalls in China. *J. Meteor. Soc. Japan,* **70,** 397–421.

Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteor. Soc.,* **106,** 447–462.

He, H., J. W. McGinnis, Z. Song, and M. Yanai, 1987: Onset of the Asian summer monsoon in 1979 and the effect of the Tibetan Plateau. *Mon. Wea. Rev.,* **115,** 1966–1995.

Ho, C.-H., and I.-S. Kang, 1988: The variability of precipitation in Korea. *J. Korean Meteor. Soc.,* **24,** 1–15.

Huang, R.-H., and L. Lu, 1989: Numerical simulation of the relationship between the anomaly of the subtropical high over East Asia and the convective activities in the western tropical Pacific. *Adv. Atmos. Sci.,* **6,** 202–214.

Joseph, P. V., J. K. Eischeid, and R. J. Pyle, 1994: Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El Niño, and sea surface temperature anomalies. *J. Climate,* **7,** 81–105.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kang, I.-S., C.-H. Ho, Y.-K. Lim, and K.-M. Lau, 1999: Principal modes of climatological, seasonal, and intraseasonal variations of the Asian summer monsoon. *Mon. Wea. Rev.,* **127,** 322–340.

——, and Coauthors, 2001: Intercomparison of GCM simulated anomalies associated with the 1997–98 El Niño event. *Climate Dyn.,* in press.

Lau, K.-M., and S. Yang, 1997: Climatology and interannual variability of the southeast Asian summer monsoon. *Adv. Atmos. Sci.,* **14,** 141–162.

LinHo, and B. Wang, 2002: The time–space structure of Asian summer monsoon–A fast annual cycle view. *J. Climate,* submitted.

Matsumoto, J., 1992: The seasonal changes in Asian and Australian monsoon regions. *J. Meteor. Soc. Japan,* **70,** 257–273.

——, 1997: Seasonal transition of summer rainy season over Indochina and adjacent monsoon region. *Adv. Atmos. Sci.,* **14,** 231–245.

Murakami, T., and J. Matsumoto, 1994: Summer monsoon over the Asian continent and western north Pacific. *J. Meteor. Soc. Japan,* **72,** 719–745.

Ninomiya, K., and T. Murakami, 1987: The early summer rainy season (baiu) over Japan. *Monsoon Meteorology,* Oxford University Press, C.-P. Chang and T. N. Krishnamurti, Eds., 93–121.

Nitta, T., 1987: Convective activities in the tropical western Pacific and their impacts on the Northern Hemisphere summer circulation. *J. Meteor. Soc. Japan,* **65,** 373–390.

Ramage, C. S., 1972: *Monsoon Meteorology.* Academic Press, 296 pp.

Rao, Y. P., 1976: Southwest monsoon. *Synoptic Meteorology, Meteor. Monogr.,* No. 1, Indian Meteorology Department, 367 pp.

Shukla, J., and M. J. Fennessy, 1994: Simulation and predictability of monsoons. *Proc. Int. Conf. on Monsoon Variability and Prediction,* Tech. Rep. WCRP-84, Geneva, Switzerland, WCRP, 567–575.

Sperber, K. R., and T. N. Palmer, 1996: Interannual tropical rainfall variability in general circulation model simulations associated with the Atmospheric Model Intercomparison Project. *J. Climate,* **9,** 2727–2750.

——, and Coauthors, 2001: Dynamical seasonal predictability of the Asian summer monsoon. *Mon. Wea. Rev.,* **129,** 2226–2248.

Tanaka, M., 1992: Intraseasonal oscillation and the onset and retreat dates of the summer monsoon over the east, southeast and western north Pacific region using GMS high cloud amount data. *J. Meteor. Soc. Japan,* **70,** 613–629.

Tao, S., and L. Chen, 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology,* C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 60–92.

Ueda, H., T. Yasunari, and R. Kawamura, 1995: Abrupt seasonal change of large-scale convective activity over the western Pacific in the northern summer. *J. Meteor. Soc. Japan,* **73,** 795–809.

Wang, B., 1994: Climatic regimes of tropical convection and rainfall. *J. Climate,* **7,** 1109–1118.

——, and X. Xu, 1997: Northern Hemispheric summer monsoon singularities and climatological intraseasonal oscillation. *J. Climate,* **10,** 1071–1085.

——, R. Wu, and K.-M. Lau, 2001: Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific–East Asian monsoons. *J. Climate,* **14,** 4073–4090.

Webster, P. J., 1987: The elementary monsoon. *Monsoons,* J. S. Fein and P. L. Stephens, Eds., Wiley Interscience, 3–32.

Wu, R., and B. Wang, 2000a: Interannual variability of summer monsoon onset over the western North Pacific and the underlying processes. *J. Climate,* **13,** 2483–2501.

——, and ——, 2000b: Multi-stage onset of the summer monsoon over the western North Pacific. *Climate Dyn.,* in press.

Xie, P., and P. A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs. *Bull. Amer. Meteor. Soc.,* **78,** 2539–2558.

Yanai, M., C. Li, and Z. Song, 1992: Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. *J. Meteor. Soc. Japan,* **70,** 319–351.

Yoshino, M. M., 1965: Four stages of the rainy season in early summer over East Asia (Part I). *J. Meteor. Soc. Japan,* **43,** 231–245.

——, 1966: Four stages of the rainy season in early summer over East Asia (Part II). *J. Meteor. Soc. Japan,* **44,** 209–217.