NOTES AND CORRESPONDENCE

Globally Unified Monsoon Onset and Retreat Indexes

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ABSTRACT

Different criteria have been used in the past to define the monsoon onset and retreat over different monsoon regions and even over different parts of the same monsoon region. Here an objective criterion is proposed to define, for the first time, globally unified summer monsoon onset (or retreat) dates using a single meteorological variable (i.e., the global daily $1° \times 1°$ normalized precipitable water data) with the threshold value being the Golden Ratio (0.618). Results are found to be consistent with those determined using long-term rainfall data over most monsoon regions. The precipitable water data have also been used to refine the definition of monsoon regions on a grid-cell-by-cell basis. The objective definitions of these basic monsoon characteristics would provide one of the necessary foundations for global monsoon research. They, along with the onset/retreat data over a 10-yr period (1988–97), would also facilitate the diagnostics and validation of global monsoon simulations.

1. Introduction

Monsoon are one of the key elements of the global climate system and strongly affects agricultural and other human activities in monsoon regions (e.g., Webster et al. 1998). The basic monsoon characteristics, such as onset, retreat, and geographical extent, have been studied for decades (e.g., Ramage 1971). The most fundamental driving mechanisms of a monsoon system include the differential heating of the land and ocean; the moist processes that determine the strength, vigor, and location of the major monsoon precipitation; and the rotation of the earth (Webster 1987). The seasonal reversal of wind direction over monsoon regions (e.g., India) has been noted for thousands of years (Warren 1987), while the attempt to understand monsoon meteorology based on physical principles began over 300 years ago (Kutzbach 1987). The onset of the summer monsoon is generally concurrent with a reversal or major change in the wind field, an abrupt rise in precipitation and water vapor, and a drastic change in other variables (e.g., kinetic energy). Partly for this reason, different criteria have been used to define the monsoon onset and retreat over different monsoon regions (Das 1987; Tao and Chen 1987; Hendon and Liebmann 1990; Douglas et al. 1993; Murakami and Matsumoto 1994; Li and Qu 1999; Wu and Wang 2000) and even over different parts of the same monsoon region (Higgins et al. 1999).

The purpose of this paper is to propose a simple, yet objective criterion to define globally unified summer monsoon onset or retreat dates using daily precipitable water data. The same data will also be used to refine the definition of monsoon regions on a grid-cell-by-cell basis. These objective definitions of monsoon onset, retreat, and extent would provide one of the necessary building blocks for global monsoon study. They, along with the onset/retreat data for 10 yr (1988–97), would also facilitate the diagnostics and validation of global monsoon simulations.

2. Data and proposed criterion

Three different datasets have been widely used to study monsoon onset and retreat in the past: surface meteorological station data (e.g., precipitation, dewpoint temperature), radiosonde data (e.g., wind field), and satellite outgoing longwave radiation (OLR) data. However, each of these datasets has serious limitations; for instance, the relationship between OLR data and precipitation over land is not as good as that over ocean; and the relationship becomes much worse at daily time scales (e.g., Xie and Arkin 1998; Wu and Wang 2000). Precipitable water (PW) data were used over the Indian Ocean during the 1979 summer monsoon (Cadet 1986). More recently, the climatological pentad (5 day) mean rainfall data, which were derived by merging the satellite estimates, surface gauge measurements, and nu-

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TABLE 1. The median, mean, 25th percentile ($q_{0.25}$), and 75th percentile ($q_{0.75}$) of the annual maximum daily PW (PW_{max}) and minimum values (PW_{min}) during the 10-yr period (1988–97) over seven 1° × 1° grid cells over Bombay, India (centered at 19.5°N, 72.5°E), the southeast coast of China (23.5°N, 114.5°E), the western North Pacific (13.5°N, 112.5°E), southern Arizona (31.5°N, 111.5°W), North Africa (15.5°N, 10.5°W), Darwin, Australia (12.5°S, 129.5°E), and South America (22.5°S, 55.5°W), respectively. These seven cells are also marked in Figs. 2 and 3.

	PW_{max} (mm)				PW_{min} (mm)			
	Median	Mean	$q_{0.25}$	$q_{0.75}$	Median	Mean	$q_{0.25}$	$q_{0.75}$
India	76	77	74	80	8	9	8	10
China	70	71	70	71	12	11	10	13
North Pacific	73	73	67	80	21	21	20	22
Arizona	45	45	44	45	3	4	3	4
North Africa	59	61	56	66	11	11	10	12
Australia	73	72	67	77	10	9	8	10
South America	52	53	51	55	10	9	8	10

merical model outputs (Xie and Arkin 1997), were used to study the rainy season of the Asian–Pacific summer monsoon (Wang and LinHo 2002).

Here we intend to use the global daily PW data on 1° × 1° grids from January 1988 to December 1997 (Randel et al. 1996). These data combine water vapor retrievals from satellite infrared and microwave sensors with radiosonde data, and hence are well-suited for the study of the short-term and intraseasonal variability of monsoon (including its onset and retreat). As mentioned earlier, the abrupt rise (or decrease) of water vapor is one of the features associated with the monsoon onset (or retreat). Furthermore, the quantitative relationship between precipitation, cloud-top temperature, and PW between 40°N and 40°S has been established (Zeng 1999).

First a normalized precipitable water index (NPWI) is defined:

$$\mathrm{NPWI} = \frac{\mathrm{PW} - \mathrm{PW}_{min}}{\mathrm{PW}_{max} - \mathrm{PW}_{min}}, \tag{1}$$

where PW is the daily precipitable water at each 1° × 1° grid, and PW_{max} and PW_{min} are the 10-yr averages of the annual maximum and minimum daily PW at each grid, respectively. Table 1 shows that, at the selected seven grid cells, the 10-yr mean and median PW_{max} values are within 2 mm, and the mean and median PW_{min} values are within 1 mm. The interquartile range (i.e., the difference between the 75th and 25th percentiles), which is a more robust and resistant measure of spread than standard deviations, varies from 1 to 13 mm for PW_{max}, and is within 3 mm for PW_{min} over different cells. In contrast, the difference of PW_{max} (or PW_{min}) over different regions can be much larger (e.g., 31 mm for PW_{max} between Bombay, India, and southern Arizona; and 18 mm for PW_{min} between the western North Pacific and southern Arizona).

Using NPWI, we propose the following objective criterion to define the globally unified summer monsoon onset (or retreat) date:

The summer monsoon onset (or retreat) date for grid cell G is defined as the first day (*d*) when NWPI is greater (or less) than the Golden Ratio (0.618) for three consecutive days in seven of the nine cells centered at cell G in day *d* or ($d \pm 1$).[1]

This criterion is objective in the sense that all parameters are fixed and hence no subjective error is involved. However, the selection of these parameters is somewhat subjective, just as in previous studies (e.g., Murakami and Matsumoto 1994; Higgins et al. 1999; Wu and Wang 2000). For instance, the National Weather Service in Arizona defines the monsoon onset date as the first day when the near-surface air dewpoint temperature is greater than 55°F (or 13°C) for three consecutive days. Higgins et al. (1999) took the first day after 1 May (when the daily precipitation is greater than 0.5 mm day^{-1} for three consecutive days) as the onset date in Arizona and New Mexico. Similarly, we consider ''three consecutive days'' in our criterion. Because the monsoon onset represents a large-scale change of weather patterns, data over multiple stations are usually used to define monsoon onset over a given region [e.g., by the Indian Meteorological Department; Mooley and Shukla (1987)]. Similarly, we consider ''nine cells'' in our criterion to help remove the spurious early onset over one or more cells due to the intraseasonal variability (e.g., in precipitation and water vapor) during the premonsoon period (Flatau et al. 2001). This would also largely remove the spurious early onset over isolated cells partly due to our use of the original (i.e., unfiltered) daily PW data. Note that, even though most previous studies used a smoothed annual cycle (e.g., of OLR) to define monsoon onset (Murakami and Matsumoto 1994; Wu and Wang 2000), their use of a single grid cell (without considering adjacent cells) might be an important reason for the spatial discontinuity in their defined monsoon onset dates (e.g., Fig. 6 of Wang and LinHo 2002).

Compared with the onset and retreat dates based on local precipitation data that are available over various

[1] If one or more of the nine grids are undefined, for example, at the edge of monsoon regions, the required number of seven is correspondingly reduced. For instance, if only seven grid cells are defined, the required number is five.

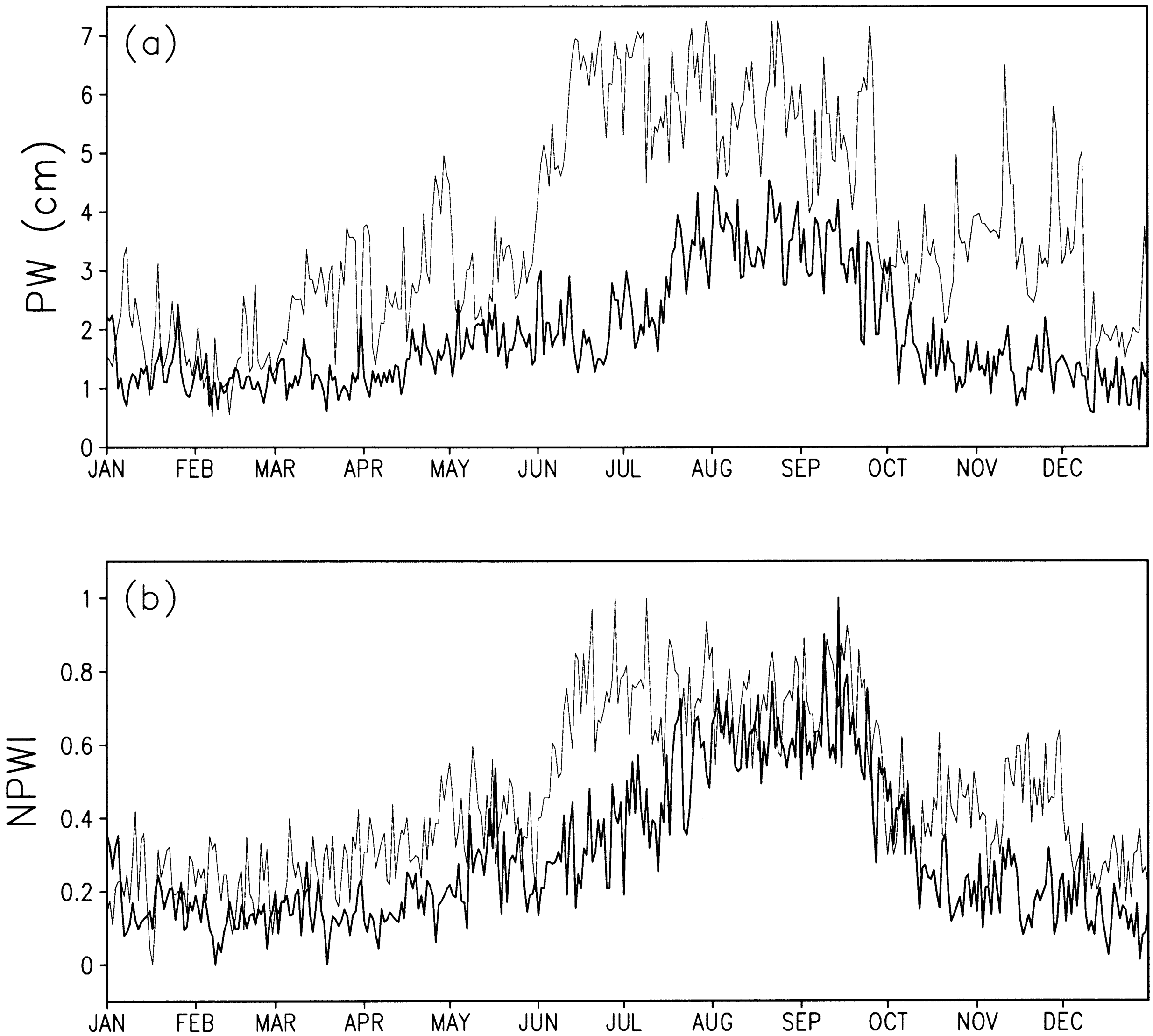

FIG. 1. (a) The 10-yr-averaged daily PW over Bombay, India (centered at 19.5°N, 72.5°E, denoted by thin lines), and over southern Arizona (31.5°N, 111.5°W, denoted by thick lines). (b) The corresponding annual cycle of the normalized PW index as defined in Eq. (1).

monsoon regions in different years, we found that the monsoon onset and retreat are always corresponding to a roughly fixed stage of the annual cycle of PW, even though both PW_{max} and PW_{min} are quite different over different regions (see Table 1). Specifically, a threshold value of 0.6–0.63 for NPWI was found to work adequately. For instance, Fig. 1 shows that the two cells in Bombay, India, and southern Arizona have significantly different PW_{max} values and hence quite different threshold PW values that mark the monsoon onset. However, these threshold PW values both correspond to a similar value of NPWI. Because the Golden Ratio [$(\sqrt{5} - 1)/2 = 0.618$] (e.g., Livio 2002) falls within the range of 0.6 to 0.63 and is, after all, present in many natural growth patterns (probably including the evolution of monsoons), it is chosen as the threshold value in our criterion. Its use here, however, does not imply that all the decimal points associated with this irrational number are needed.

3. Results

a. Geographic extent of monsoon

As mentioned earlier, over monsoon regions where PW is relatively high during the wet summer and relatively low during the dry winter, the use of NPWI leads to a single threshold value (i.e., the Golden Ratio) in our criterion. Over nonmonsoonal regions with relatively small ($PW_{max} - PW_{min}$), however, the use of NPWI may amplify small variations in PW. Also, some nonmonsoonal regions (e.g., Illinois) have a relatively large ($PW_{max} - PW_{min}$) and an abrupt rise of PW in early summer. In both of these nonmonsoonal regions, our criterion would give spurious monsoon onset and retreat dates. Therefore, PW itself is not sufficient to distinguish between monsoonal and nonmonsoonal regions, and our criterion should be applied to monsoon regions only.

A consensus on the global geographical extent of monsoon has not been reached yet. Using a rather strict definition of a monsoon based on both wind reversal and seasonal precipitation criteria, Ramage (1971) identified only African, Asian, and Australian regions as monsoon regions (35°N–25°S, 30°W–170°E). Higher latitudes over east Asia have also been included in recent studies (e.g., Wang and LinHo 2002). Later, justification was given for considering North America as a monsoon region based on the seasonal precipitation criterion and the seasonal surface wind reversal over some areas (Douglas et al. 1993; Higgins et al. 1999). Zhou and Lau (1998) also suggested that South America qualifies as a monsoon region based on the seasonal precipitation criterion and the fact that the wind reversal becomes apparent after the strong annual mean wind is removed. These studies, however, are not sufficient for our analysis of the $1° \times 1°$ PW data, because we need to define monsoon regions on a grid-cell-by-cell basis. For instance, the exact geographic extent of monsoon over South America was not given by Zhou and Lau (1998). In contrast, the monsoon regions as defined by Ramage (1971) contain many nonmonsoonal cells over the interior of the Sahara Desert, over the Tibetan Plateau, and near the equator.

To refine the definition of monsoon regions on a grid-cell-by-cell basis, we first compute the 10-yr-averaged monthly PW over each cell. Then we obtain the maximum monthly PW during the three summer months [e.g., June–August in the Northern Hemisphere (NH), denoted as PW_w], and the maximum monthly PW during the three winter months (e.g., December–February for the NH, denoted as PW_c). The refined monsoon regions are simply defined as grid cells that are within the monsoon regions given in the above studies and have a difference between PW_w and PW_c greater than 12 mm. Initially we have also tried to use the annual maximum and minimum monthly PW values. They would give similar results over known monsoon regions with relatively high PW during the wet summer and relatively low PW during the dry winter. However, they would also include some nonmonsoonal regions, particularly over the equatorial regions (figure not shown). For instance, for a grid cell centered at (2.5°S, 10.5°W) over the equatorial Atlantic, the difference between the annual maximum (50 mm in April) and minimum (30 mm in July) monthly PW values is as large as that over monsoon regions (e.g., Fig. 1). In contrast, the difference between PW_w (45 mm in February) and PW_c (34 mm in June) is less than 12 mm, and hence this grid cell is defined as nonmonsoonal.

The monsoon regions defined in this way are indicated as unshaded areas in Figs. 2 and 3. Grid cells over the Sahara Desert and the Tibetan Plateau are correctly masked. Similarly, cells over the Sierra Madre Occidental in Mexico are masked, even though the number of shaded cells seems to be slightly larger than indicated in Higgins et al. (1999). Also shaded are nearly all cells between 8°N and 8°S, including some regions with well-known seasonal reversal of wind direction (e.g., along the coast of Somalia). This is not surprising, because monsoon regions that are defined based on wind versus precipitation data could also be different. The geographic extent of the South American monsoon was not provided in Zhou and Lau (1998), and is shown to be relatively small compared with other known monsoon regions in Figs. 2 and 3. Most of the continental United States, the Gulf of Mexico, and southern Africa have ($PW_w - PW_c$) greater than 12 mm, but they are generally regarded as nonmonsoonal from previous studies and hence are shaded as well.

b. *Monsoon onset and retreat dates*

Figures 2 and 3 show the global distribution of median monsoon onset and retreat dates during the 10-yr period. In the NH, the onset of the summer monsoon starts in early to mid-May [Julian Day (JD) 120–140] and reaches the edge of different monsoon regions by mid-July (around JD190). The summer monsoon commences withdrawal in early September (JD250), and retreats from most monsoon regions by late October (JD300). In the Southern Hemisphere, the corresponding onset and retreat dates differ from those in NH by about 6 months.

In general, summer monsoon onset is associated with the dry to wet transition (e.g., in precipitation, PW, or OLR) and the wind direction reversal. Over a specific area, however, the exact onset dates based on dry to wet transition and wind reversal are not necessarily simultaneous; rather, they could be significantly different (e.g., Das 1987; Webster 1987; Murakami and Matsumoto 1994; Wang and LinHo 2002). The PW is primarily related to the dry to wet transition, and our results should be compared primarily with those based on precipitation or OLR data.

In Asia, the summer monsoon occurs first in a band across the Indochina peninsula in early May (JD120–130), consistent with results based on the OLR data (Wu and Wang 2000). It then progresses northwestward into the Indian subcontinent (through the Bay of Bengal), northward in east Asia, and eastward in the western North Pacific (including the South China Sea and the Philippine Sea). The summer monsoon arrives in southern India in late May (JD140–150), rapidly spreads to most of the country within 30 days, and reaches the foothills of the Tibetan Plateau in early July (around JD180). It commences withdrawal in early September (around JD250) and retreats from most of the continent

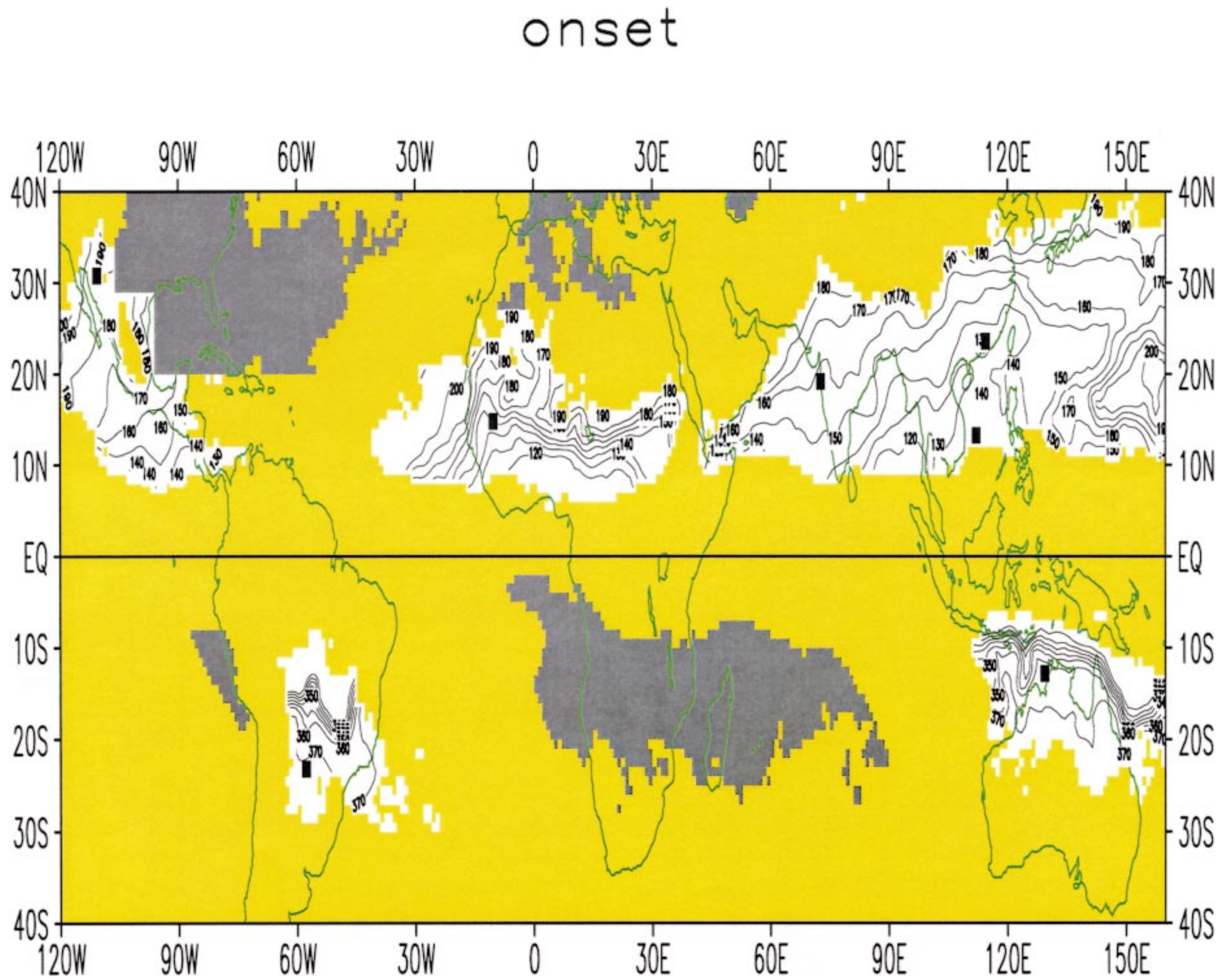

FIG. 2. The global distribution at 1° × 1° resolution of the median dates (in Julian day) of summer monsoon onset between 1988 and 1997. A number (n) greater than 365 represents the Julian day ($n - 365$) in the following year. Monsoon regions are indicated by unshaded grid cells, and the seven cells used in Tables 1 and 2 are also marked. Yellow (or gray) shades indicate nonmonsoonal grid cells with relatively small (or large) annual cycle of PW.

(except south peninsular India) by mid-October (JD290–300). The onset and withdrawal patterns in India as shown in Figs. 2 and 3 are nearly the same as those prepared by the Indian Meteorological Department based on average pentad rainfall data (Mooley and Shukla 1987). Table 2 shows that the average onset (or retreat) dates over Bombay, India, are within two days of those given in Mooley and Shukla (1987).

In east Asia, Fig. 2 shows that the summer monsoon advances to southern China in mid-May (JD130–140; also Table 2), and reaches the Yangtze River valley in mid-June (JD160–170) when the mei-yu (i.e., so-called plum rain) in the valley and the baiu in Japan begin. Then the monsoon progresses slowly northward for the next three weeks to cover part of northern China, South Korea, and Japan, consistent with the stagnant mei-yu front. Figure 3 shows that the monsoon starts withdrawal in early September (around JD250), and rapidly retreats from the mainland of China in a month. These results over east Asia are nearly the same as those determined using long-term rainfall records (Tao and Chen 1987).

Just as in east Asia, the summer monsoon progression is stepwise in the western North Pacific. It rapidly spreads to the South China Sea and the Philippine Sea by mid- to late May (JD130–150), followed by slow eastward movement until early July (JD190). Then it advances rapidly eastward again. This stepwise progression is consistent with those using the pentad satellite precipitation data (Wang and LinHo 2002). Table 2 shows that, at the grid cell centered at (13.5°N, 112.5°E) over the South China Sea, our onset date of JD139 is close to their pentad 37 (JD 133). The earlier onset over the northern (than over the southern) South China Sea is also consistent with Lau et al. (2000). Over the eastern Philippine Sea, however, these results based on PW or precipitation are significantly different from

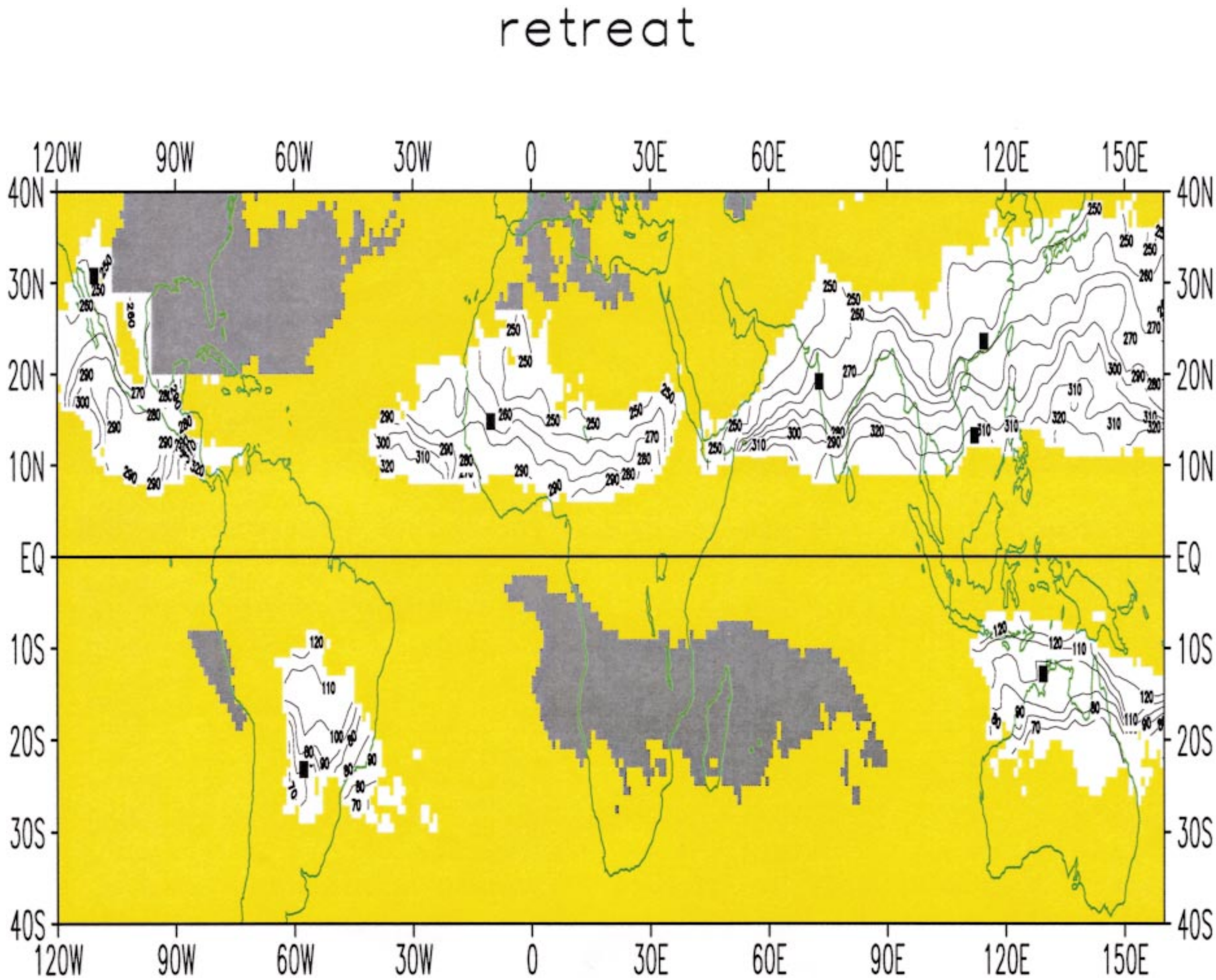

FIG. 3. Same as in Fig. 2 except for the median dates (in Julian days) of summer monsoon retreat between 1988 and 1997.

those based on the OLR data in Murakami and Matsumoto (1994). Figure 3 shows that the monsoon begins withdrawal from the western North Pacific by mid-October (JD280–290), and retreats from this region by mid-November (JD320). The overall patterns of monsoon retreat using the daily PW data (Fig. 3), pentad satellite precipitation data (Wang and LinHo 2002), or pentad OLR data (Murakami and Matsumoto 1994) are somewhat different. For instance, Table 2 shows that our median retreat date around (13.5°N, 112.5°E) is JD312, while Wang and LinHo (2002) gave pentad 67 (JD333).

TABLE 2. The median, mean, 25th percentile ($q_{0.25}$), and 75th percentile ($q_{0.75}$) of the summer monsoon onset and retreat dates during the 10-yr period (1988–97) over the same seven grid cells as in Table 1. The values in parentheses are the corresponding onset/retreat dates from Mooley and Shukla (1987) (over India), Tao and Chen (1987) (China), Wang and LinHo (2002) (the North Pacific), Higgins et al. (1999) (Arizona), and Hendon and Liebmann (1990) (Australia).

	Onset date				Retreat date			
	Median	Mean	$q_{0.25}$	$q_{0.75}$	Median	Mean	$q_{0.25}$	$q_{0.75}$
India	159 (161)	158	155	162	271 (271)	271	257	286
China	131 (130)	132	122	139	268	267	258	276
North Pacific	139 (133)	139	132	147	312 (333)	315	296	336
Arizona	188 (187)	191	186	198	249	250	246	251
North Africa	151	156	143	171	267	271	261	285
Australia	362 (359)	341	305	362	99	96	92	104
South America	9	14	6	16	56	62	47	86

The North American monsoon system (NAMS) refers to the monsoon over Mexico and the southwestern United States (Douglas et al. 1993; Higgins et al. 1999). Figure 2 shows that the summer monsoon actually starts from Central America in late May (JD140–150), reaches southern Mexico by early June (JD160), and advances to the southwestern United States by early July (JD190). It begins withdrawal by early September (JD250), and retreats from North America in 1 month (Fig. 3). These results are consistent with those based on long-term in situ precipitation data (Higgins et al. 1999). For instance, over southern Arizona (31.5°N, 111.5°W), our median onset date is JD188 versus JD187 in Higgins et al. Both are also consistent with JD186 as determined by the National Weather Service in Arizona using the dewpoint temperature data. Note that while different threshold values and durations were used over southwestern United States, northern Mexico, and southern Mexico, respectively, in Higgins et al., all parameters remain the same globally in our criterion.

Over North Africa, Fig. 2 shows that the summer monsoon onset occurs in early May (JD120–130) and advances northward slowly toward the southern edge of the Sahara Desert in the interior of the continent. Only over West Africa, does the monsoon advance northward well beyond 15°N. The monsoon starts withdrawal by mid-September (JD250) and retreats from the continent in a month (Fig. 3). Table 2 indicates that the median onset and retreat dates at the grid cell centered at (15.5°N, 10.5°W) are JD151 and JD267, respectively.

Over Australia and Indonesia, Fig. 2 shows that the summer monsoon sets in by early November (JD310) and reaches northern Australia by late December and early January (JD370). Its withdrawal starts by early March (JD70) and terminates by late April (JD120) (Fig. 3). Compared with the average onset date (JD359) in Darwin (12°S, 130°E) based on local rainfall and wind data (Hendon and Liebmann 1990), our median onset date is very close (JD362), while the average date using the pentad OLR data (Murakami and Matsumoto 1994) is much earlier (around JD328 from their Fig. 3).

Over subtropical South America, Fig. 2 shows that the summer monsoon occurs in early November (around JD310) and advances slowly southward until mid-December (JD350). It then spreads rapidly and reaches the coast of southern Brazil in early January (JD370). The monsoon withdrawal starts in mid-March (around JD80) and ends in late April (JD120).

4. Conclusions and further discussions

Wind, precipitation, and OLR data have been traditionally used for monsoon research. Here daily PW data are introduced as a new global variable to study monsoon onset and retreat. Furthermore, a simple, yet objective criterion based on daily PW is proposed to define summer monsoon onset and retreat dates over different monsoon regions in the world. Overall, the results are consistent with those using local precipitation data over most monsoon regions. Over the western North Pacific and particularly over the eastern Philippine Sea, monsoon retreat (and to certain degree onset) dates are calculated to be quite different, depending on the use of daily PW data, pentad satellite precipitation data (Wang and LinHo 2002), or pentad OLR data (Murakami and Matsumoto 1994). This disagreement suggests the need for further study using in situ data (e.g., buoys). Over Australia, the daily PW data and pentad OLR data (Murakami and Matsumoto 1994) also give different onset and retreat dates. Furthermore, Table 2 shows a difference of 20 days between the median and mean onset dates over this region and an interquartile range of 57 days of the onset dates during the 10-yr period. These large differences may be related to the inherent difficulty in distinguishing premonsoon activities from monsoon onset over this region (e.g., Hendon and Liebmann 1990).

The geographic extent of monsoon regions has been defined by various researchers in the past, but it is difficult to apply their results to individual $1° \times 1°$ grid cells. Even though PW itself is not sufficient to distinguish between monsoonal versus nonmonsoonal regions, its use over grid cells within the monsoon regions identified in previous studies enables us to refine the definition of monsoon regions on a grid-cell-by-cell basis, as indicated by the unshaded regions in Figs. 2 and 3. In particular, our study provides the geographic extent of the South American monsoon that was not determined in previous studies (e.g., Zhou and Lau 1998). While southern Africa, most of the continental United States, and the Gulf of Mexico are generally regarded as nonmonsoonal, they still have relatively large annual cycle of PW and well-defined dates for the abrupt increase of PW in early summer and decrease of PW in early fall. We are currently analyzing the daily precipitation and PW data over North America to compare and understand the relationship between precipitation and PW over Mexico and the southwestern United States versus that over other nonmonsoonal regions.

In general, the temporal variation of precipitation, water vapor, and wind fields during the summer monsoon retreat is less drastic than that during the monsoon onset. It is also difficult to distinguish the summer monsoon retreat from the winter monsoon onset. Therefore, the summer monsoon retreat dates (particularly over low latitudes) using the PW (Fig. 3), satellite precipitation (Fig. 8 of Wang and LinHo 2002), or OLR data (Fig. 3 of Murakami and Matsumoto 1994) may not be as reliable as the onset dates, and hence should be used with caution.

It needs to be emphasized that monsoon onset and retreat dates may vary significantly from year to year at some locations. For instance, Table 2 shows that the interquartile range of onset dates between 1988 and 1997 varies from 7 to 57 days in seven $1° \times 1°$ grid cells selected over different monsoon regions. The interquartile range of retreat dates also varies from 5 to 40 days. Considering the observed large interannual variability in monsoon onset and retreat (e.g., Mooley and Shukla 1987) and results in Table 2, the interannual variability in monsoon onset and retreat dates based on 10 yr worth of PW data in our study should be viewed as preliminary and updated whenever longer-term data become available. Furthermore, while the unified criterion in this paper provides a necessary building block for global monsoon study, much work is still needed to provide additional insights (from the PW seasonal variation) about the operation of monsoon system. As an example, work is currently under way to understand the impact of various factors (e.g., El Niño) on the interannual variability of the monsoon onset and retreat dates and the potential value of this interannual variability in predicting summer precipitation over monsoon regions.

Another potential application of our results is the evaluation of global monsoon simulations. Most climate models are deficient in simulating global monsoons (e.g., Sperber and Palmer 1996). While monsoon precipitation and circulations have been emphasized in model evaluations, global monsoon onset and retreat in model simulations have not received much attention. The simple and objective definitions of monsoon onset, retreat, and extent in this paper can be directly applied to the daily PW output of any global model. Model results can then be evaluated using the monsoon onset and retreat data here.

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