A Global-Scale Examination of Monsoon-Related Precipitation

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ABSTRACT

A pentad version of the Global Precipitation Climatology Project global precipitation dataset is used to document the annual and interannual variations in precipitation over monsoon regions around the globe. An algorithm is described that determines objectively wet season onset and withdrawal for individual years, and this tool is used to examine the behavior of various characteristics of the major monsoon systems. The definition of onset and withdrawal are determined by examining the ramp-up and diminution of rainfall within the context of the climatological rainfall at each location. Also examined are interannual variations in onset and withdrawal and their relationship to rainy season precipitation accumulations. Changes in the distribution of ''heavy'' and ''light'' precipitation events are examined for years in which ''abundant'' and ''poor'' wet seasons are observed, and associations with variations in large-scale atmospheric general circulation features are also examined. In particular, some regions of the world have strong associations between wet season rainfall and global-scale patterns of 200-hPa streamfunction anomalies.

1. Introduction

In this paper we examine the characteristics of precipitation over monsoon regions around the globe using a recently developed pentad version of the Global Precipitation Climatology Project (GPCP; Xie et al. 2003) global rainfall analyses. Several characteristics of rainfall in these regions are examined; these include the climatological and interannual variability of rainy season onset and withdrawal, and associations of rainy season precipitation with atmospheric circulation features. We also examine variations in the frequency of pentads with ''light'' and ''heavy'' rainfall during abundant and poor wet seasons.

The use of precipitation data alone to define monsoon onset and withdrawal violates the strict definition of monsoon systems, a definition in which precipitation changes are subordinate to circulation changes (e.g., Ramage 1971; Drosdowsky 1996). By the same token, the India Meteorological Division uses pentad precipitation from rain gauges to define monsoon onset and withdrawal over the Indian subcontinent (Rao 1976). The view taken in this paper is from a global perspective, that is, the notion of a ''global monsoon,'' in which precipitation maxima migrate between the Northern and Southern Hemispheres in association with the continental heating by the sun. Despite ''philosophical'' differences in the definition of monsoon onset and withdrawal, the time of onset and withdrawal of monsoon systems is not greatly different in many regions when based on precipitation data rather than as defined in the classical sense. More to the point, however, it is the precipitation associated with the monsoon that has the most impact on the people, plants, and animals that live in these regions. To avoid any misunderstanding, when we refer to onset and withdrawal from here on we specifically mean with respect to the rainy season and not necessarily atmospheric circulation changes related to monsoon systems.

Various others have developed schemes to define rainy season onset and withdrawal. Kousky (1988) used outgoing longwave radiation (OLR) as a proxy for tropical rainfall to document the rainy season onset and withdrawal in South America. Similarly, Wang (1994) used OLR and highly reflective cloud (HRC) data to investigate onset and withdrawal of the Austral–Asian monsoon system. Higgins et al. (1997) used rain gauge data to define summer monsoon onset over the southwestern United States. Marengo et al. (2001) used a combination of rain gauge data, OLR, and model analyses to define monsoon onset and withdrawal over South America.

There have been many recent studies of the Indian and Southeast Asian monsoon systems. Webster and Yang (1992) defined a dynamical monsoon index based on the vertical shear of the zonal wind to measure the broad-scale feature of the Asian monsoon. Later, Goswami et al. (1999), Wang and Fan (1999), and Lau et al. (2000) constructed several indices to measure the

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circulation features associated with the South, Southeast, and East Asian monsoon components. Lau and Yang (1997) described the features associated with the sudden onset of the Southeast Asian monsoon, especially that over the South China Sea. Qian and Yang (2000) determined the onset of Southeast Asian monsoon using upper-tropospheric water vapor band brightness temperature, which the authors claimed is more appropriate than OLR in representing convective precipitation in both the Tropics and extratropics.

One of the primary motivations for this work is to demonstrate the utility of the GPCP pentad dataset. The 5-day temporal resolution that it affords makes it possible to define onset and withdrawal of ''wet season'' precipitation around the globe. It also permits quantitative examinations of onset and withdrawal over oceans as well as land because satellite estimates of rainfall are incorporated into the dataset as well as observations from rain gauges. Because of the relatively coarse resolution of these data (pentad, 2.5° latitude–longitude spatial resolution) we expect to portray only a macro view of the characteristics of wet season rainfall. Despite this limitation, however, this coarse view is truly global in scope and not limited to land regions only.

2. Data

The precipitation data used for this study were obtained from the Global Precipitation Climatology Project (Arkin and Xie 1994). The monthly GPCP analyses are formed by combining various estimates of precipitation from satellite data with rain gauge data (Huffman et al. 1997). However, monthly data do not afford the time resolution that is necessary to define rainy season onset and withdrawal, so a new pentad version GPCP product is used (Xie et al. 2003). The pentad (i.e., 5-day mean) data spans the period 1979 to present (but only 1979–99 data used here) and has a spatial resolution of 2.5° of latitude and longitude.

The pentad GPCP product was adapted from an existing pentad version of the Climate Prediction Center (CPC) Merged Analysis of Prediction (CMAP) analysis (Xie and Arkin 1997). Because there are differences in the GPCP and CMAP monthly analyses (particularly over the oceans), two important constraints were imposed on the generation of the pentad GPCP dataset to ensure that the pentad and monthly versions of the GPCP analyses were consistent. First, the pentad amounts were adjusted so that they summed as near as possible to the GPCP monthly accumulations. Second, when applying the adjustment, care was taken to ensure that the temporal variability that is inherent in the pentad data was preserved (Xie et al. 2003).

Atmospheric circulation data that are used in this study are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (Kalnay et al. 1996), referred to colloquially as Reanalysis-1. Specifically, 200-hPa streamfunction fields are used. Because this field represents large-scale characteristics of the atmosphere, little, if any, differences in this field are observed in the Reanalysis-2 (Ebisuzaki et al. 1999) streamfunction fields.

3. Rainy season onset and withdrawal

Harmonic analysis applied to the climatological mean pentad GPCP data (Fig. 1, top) reveals regions around the globe that have a pronounced wet and dry season. The amplitude of the first harmonic exceeds 2 mm day^{-1} over the main tropical convective regions of Africa, the Americas, and the Australasian region, but also over the midlatitudes of the northeast Pacific including the western coast of the United States. A striking difference in this regional midlatitude behavior compared to the Tropics is that the phase of the maximum occurs during boreal winter rather than during the high-sun season (Fig. 1, bottom). We limited the computation of rainy season onset and withdrawal to those regions where the amplitude of the first harmonic is 1.0 mm day^{-1} or greater and where the amplitude of the first harmonic exceeds that of the second. Thus we used the results of the harmonic analysis as a guide to determine the regions that have a single, dominant wet season, which is a strong indication of where monsoon regimes exist. The first criterion was relaxed to 0.1 mm day^{-1} or more over North America so that the North American monsoon system would be apparent in the analysis.

a. Onset and withdrawal algorithm description

Our objective definition of wet season onset is the first occurrence of four consecutive pentads during which the individual pentad precipitation accumulation in three of the four exceeds 33% of the climatological rainy season mean precipitation accumulation. If the first pentad of the four does not exceed that threshold, then onset is defined as beginning with the second pentad in that group of four pentads. Similarly, we define wet season withdrawal as the first pentad after onset in a sequence of five consecutive pentads during which the precipitation during each pentad is below 33% of the climatological rainy season mean precipitation accumulation. The dates of onset and withdrawal that are computed by the method described above will obviously change depending on the choices of length or threshold. We experimented with several variations of these definitions, and the method stated above yielded the best characteristics, in our opinion, of depicting time of onset and withdrawal without being fooled by short-lived precipitation anomalies. We determined this by visually comparing time series of pentad rainfall for individual years at various locations with the computed results of the algorithms.

Because we define onset and withdrawal using pentad data, the dates that are plotted in Figs. 3 and 4 are the

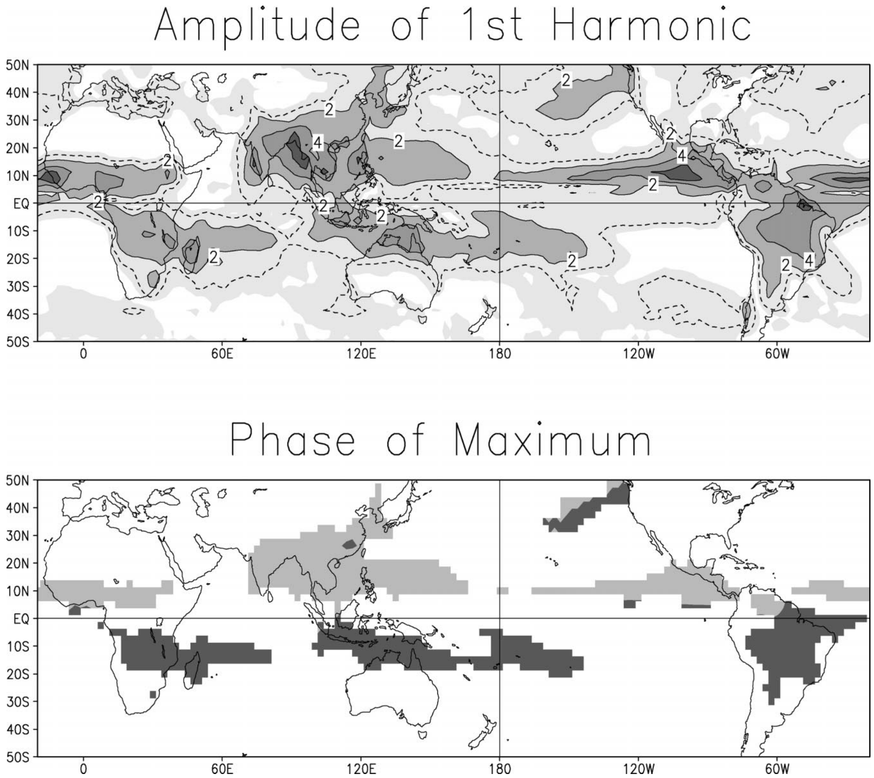

FIG. 1. (top) Amplitude and (bottom) phase of maximum amplitude of the first harmonic of pentad GPCP precipitation over the period 1979–99. Amplitude units are mm day^{-1} and values above 0.5 mm day^{-1} are shaded; the dashed line represents an amplitude of 1 mm day^{-1}. Dark (light) shading in phase plot means that maximum amplitude of the 1st harmonic occurs between Dec and Feb (Jun and Aug).

midpoints of a pentad. Onset and withdrawal were computed for each year of the GPCP pentad dataset (1979–99). Climatological onset and withdrawal are defined here as the mean of the onset and withdrawal pentads of the individual years over the 21-yr period.

b. Comparisons with other studies

As a means to validate our algorithm, we compared the results with those of previous work. Specifically, we compared our climatological mean onset and withdrawal dates with the landmark work of Rao (1976) who documented extensively the Indian monsoon. We also show a comparison of our results with those of Higgins et al. (1997) over the North American monsoon region.

Although the Indian summer monsoon system is an integral part of the Australasian monsoon system, we examine the characteristics of monsoon onset and withdrawal over India alone in this section because it is probably the most thoroughly documented such system on earth. Because of that, it provides an established benchmark by which our methodology to monitor monsoon onset and withdrawal can be assessed. The climatological mean monsoon onset and withdrawal dates over India from Rao (1976) shown in Fig. 2 (which is an adaption of his Fig. 3.1) are compared with the climatological mean onset and withdrawal dates for the Indian summer monsoon based on the algorithm described above (Fig. 3). For both onset and withdrawal, the results of Rao are based on ''. . . the rather sharp increase and decrease respectively shown by the 5-day means of rainfall and the changes in the circulation'' (Rao 1976). The two analyses agree reasonably well in that they both depict a southeast to northwest progression of onset with similar characteristics in the gradient and the reverse for withdrawal. There are differences, however, particularly in the southwestern portion of the region where the orientation of onset advance is from southwest to northeast in our analysis. This is likely 1) due to the influence of data over the Arabian Sea and Bay of Bengal that are in the GPCP analyses but obviously not in the Indian rain gauge analyses, and 2) because Rao uses general circulation data as well as rainfall in his onset and withdrawal definitions. The mean dates of withdrawal are also quite similar between the two analyses. Most notably, both analyses depict a considerably slower withdrawal compared to onset over much of the subcontinent. But the most significant difference between the two analyses is the availability of information over the ocean in the GPCP results; note

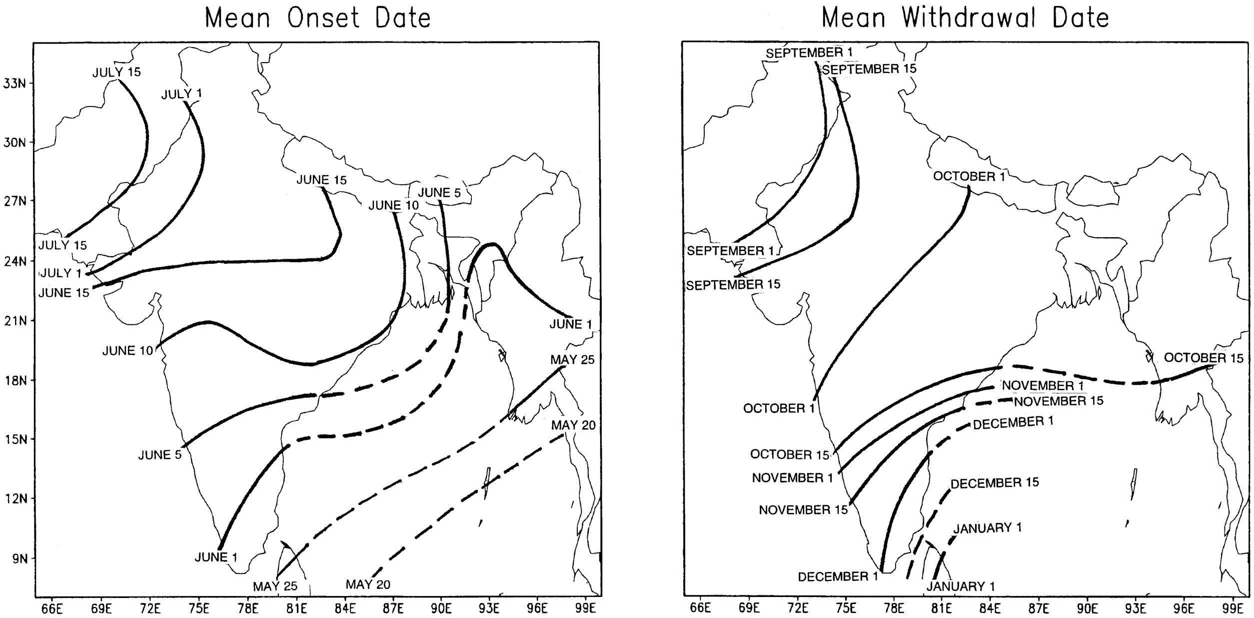

FIG. 2. Mean onset and withdrawal dates for Indian monsoon adapted from Rao (1976) who compiled these results using pentad accumulations of rain gauge and circulation data. Dashed lines indicate extrapolations over the oceanic regions.

that the dashed lines over the ocean in the analyses of Rao indicate that the data are extrapolated there. This is not an innovative feature, however, as Lau and Yang (1997) and Qian and Yang (2000) also show dates of monsoon onset over water based on remotely sensed precipitation information using the Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI; Arkin and Meisner 1987) and the CMAP precipitation estimates (Xie and Arkin 1997), respectively.

The magnitude of the precipitation associated with the North American monsoon pales in comparison to that of the Indian monsoon. Despite that fact, there is an annual sudden wet season onset during summer in that region that is well defined and documented by Higgins et al. (1997). Over the ‘‘pure’’ monsoon area of Arizona and western New Mexico, their study showed that the average date of onset is 7 July, having used the criteria to define onset as the first date after 1 June when their precipitation index was at least $+0.5$ mm day^{-1} for three consecutive days. The climatological onset for that area from the algorithm described in this paper is 5 July in the extreme eastern portion of that area and 15 July in the extreme western part (Fig. 4, top left). Of course, since we are using pentad data, a specific date cannot be determined but we feel that the closeness of our result to the detailed analysis of Higgins et al. gives additional credence to our methodology.

4. Synopsis of the characteristics of wet season rainfall over the globe

a. Onset and withdrawal

The climatological advance and retreat of wet season rainfall is relatively smooth over all regions except for the Asian region east of India. The orientation of onset and withdrawal is generally meridional over the interior of Africa, most of India, southern Mexico and Australasia with onset proceeding in the poleward direction and withdrawal the reverse (Figs. 3, 4). Closer to the coasts, however, the progression of onset tends to be parallel to the coastline. In contrast, the progression of onset proceeds from east to west over northeastern India, northern Mexico, and the southwestern United States while withdrawal is generally north to south over these regions.

Over the continental portion of the East Asia region, the general pattern of advance of wet season onset is poleward, but the pattern is considerably more diffuse and irregular compared to most other regions around the globe. Over the oceanic portion of this region west of the Philippines, the character of the advance and retreat of wet season precipitation is considerably more like that observed over most other monsoon regions and is more closely associated with the migration of the intertropical convergence zone (ITCZ). Over the South China Sea, the direction of onset appears to proceed in the opposite direction (equatorward), which is an observation that has been reported by others (Qian and Wang 2000) that argue that monsoon onset over the northern South China Sea is influenced by midlatitude systems and is the first stage of the much broader Asian summer monsoon. Note, however, that monsoon withdrawal proceeds in the expected equatorward direction over this region. The pattern of onset that we have presented is considerably different from the pattern in Lau and Yang (1997), who defined the northern limit of monsoon onset as the first pentad of the year when clima-

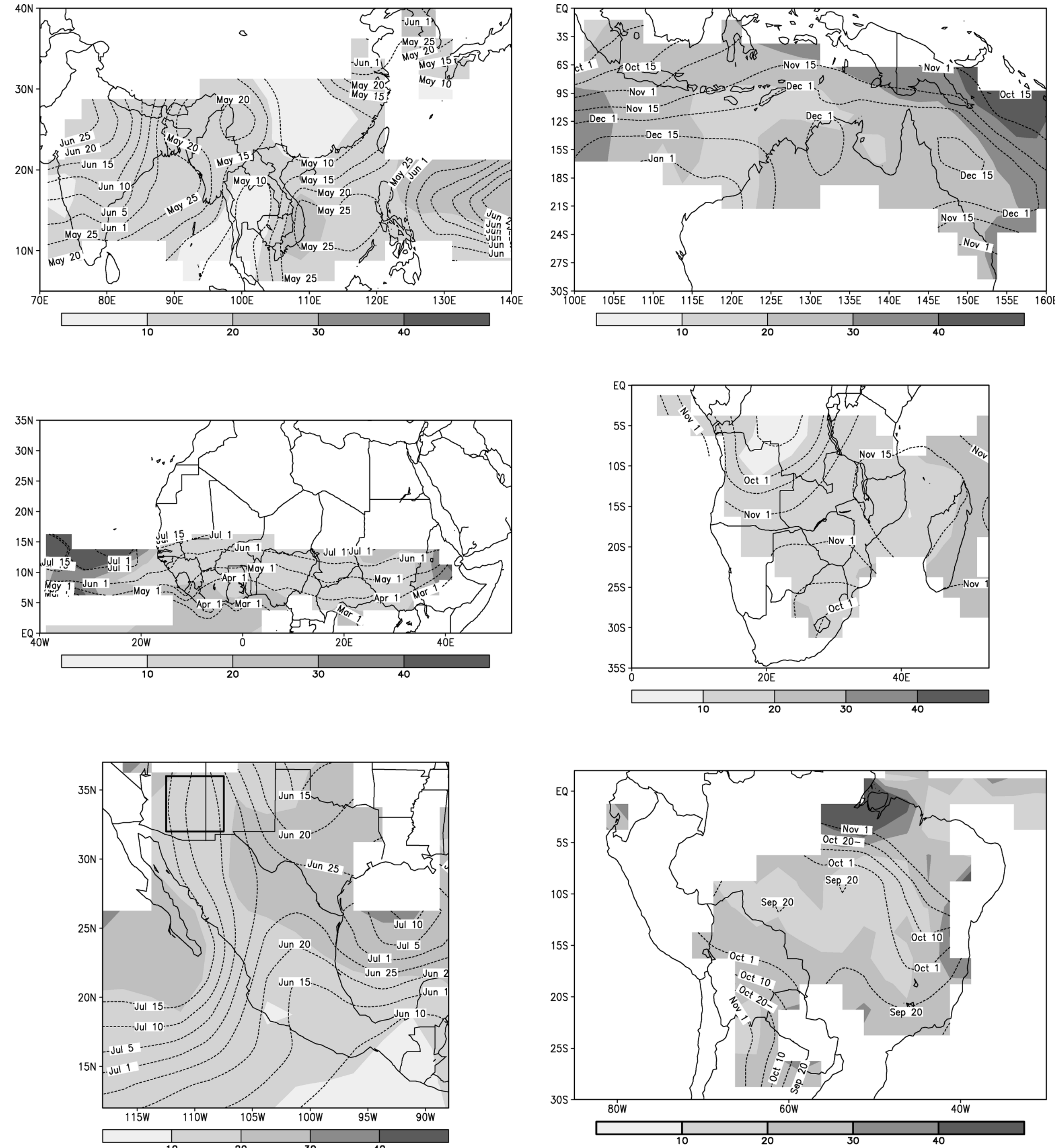

FIG. 3. Twenty-one-year mean (1979–99) of wet season onset date (contours). Shading depicts the standard deviation (in days) of the onset dates. The box drawn over the southwestern United States (lower left) depicts the region used by Higgins et al. (1997) in their study of the North American monsoon.

tological GPI rainfall rate was 6 mm day^{-1}. However, as stated in their paper, the Asian region is complex and the monsoon system is composed of three interlinked monsoons: South Asian, Southeast Asian, and East Asian. In addition, the complex character of the Asian monsoon is likely associated with the interaction among extratropical features during the transition from spring to summer, such as the mei-yu (Chinese nomenclature; known as baiu in Japan and mae-ue in Korea), which has four distinct stages of development and demise (Yoshino 1971). Furthermore, the computation of onset and withdrawal dates depends upon how one defines these features.

Over South America, wet season onset occurs between

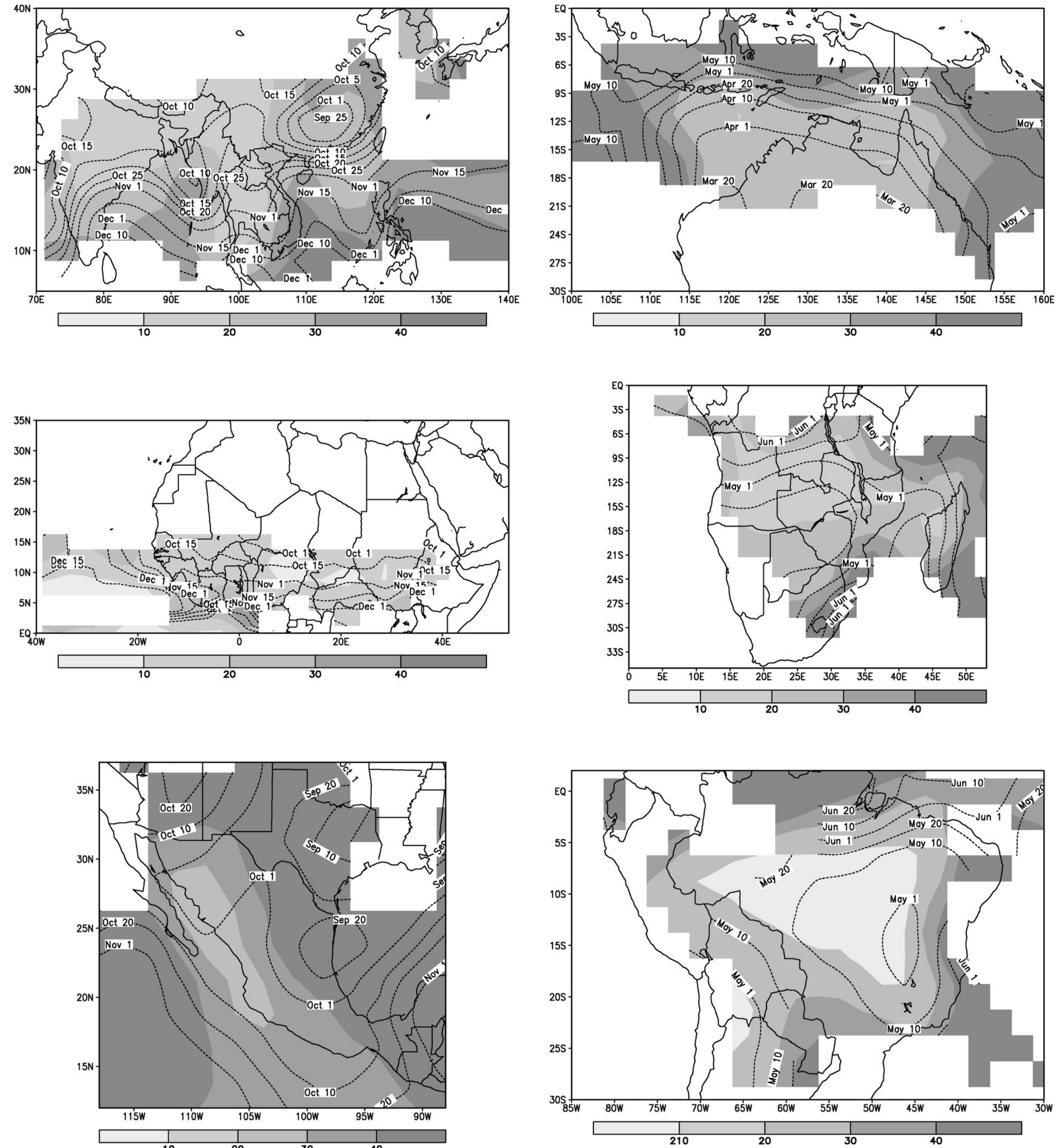

FIG. 4. As in Fig. 3 except for withdrawal date.

20 September and 1 October over most of southwest Brazil and northern Bolivia and appears to advance almost simultaneously from that region toward northeast Brazil and southwest toward southern Bolivia, southern Paraguay, and northern Argentina. Thus the advance of onset appears to emanate bidirectionally from an area well south of the equator (10°–15°S) toward the northeast and southwest, which is quite different from the classic advance of onset in most other regions. Withdrawal of the wet season tends to be observed earliest in southeastern interior Brazil centered near 15°S, 45°W with later withdrawal dates emanating in all directions from that location, although the retreat is primarily equatorward as expected. This behavior is similar to what Marengo et al. (2001) found by using pentad OLR as a proxy for rainfall. The lack of onset/withdrawal information in the northwest sections of the plots is due to the fact that two seasonal rainfall maxima occur in that region.

b. Variability of monsoon onset and withdrawal

The standard deviation of onset and withdrawal dates over the 1979–99 period is presented graphically as the shaded portions of Figs. 3 and 4, respectively. Variability in the time of withdrawal is larger than for onset over most regions. The exceptions are over South America and over northern tropical Africa.

The least variability with regard to wet season onset occurs over much of China and portions of Southeast Asia where the standard deviation over the 21-yr study period is 10 days or less. Relatively low variability of monsoon onset is observed over India, the Bay of Bengal, interior Brazil, and northern tropical Africa where the standard deviation is 10–20 days. In contrast, the largest variability in onset occurs in the Austral–Asian domain where the standard deviation in onset is about 20–30 days. The largest variation in the time of monsoon withdrawal (20–40 days) is also observed over the Austral–Asian region and over North America. Conversely, most of northern tropical Africa, continental India, and the western portion of Southeast Asia have the least variability in wet season withdrawal (10–20 days).

The most variability in both onset and withdrawal occurs over the North American and Australasian domains. One reason for this may be due to the different distribution of land and sea over these regions compared to the African, South American, and Asian monsoon regions. Because Africa and South America are large landmasses, much of which resides in the Tropics, the intense land surface heating during the high-sun season results in a large-scale meridionally oriented thermally direct circulation that is difficult to perturb, thus interannual variations in onset and withdrawal tend to be small. Similarly, the heating over the vast Asian continent during summer combined with the relatively cooler ocean surface temperatures to the south results in an annual meridionally oriented thermally direct circulation that is a dominant annual feature. In contrast, there is comparatively little tropical land surface over North America and Australasia, and the size of the extratropical landmasses are much less extensive compared to the Asian continent. Therefore, the subsequent weaker circulations are more likely to be perturbed by external influences such as midlatitude interactions and the modulation of large-scale surface heating by surrounding ocean areas. Another potential source for explaining the interannual variability in monsoon onset and withdrawal may be El Niño–Southern Oscillation (ENSO) phenomena, which affects the land–sea temperature contrasts and thus influences the large-scale thermally direct atmospheric circulations that may result in accelerated or delayed monsoon onset and withdrawal.

c. Wet season length and the contribution to annual total precipitation

We define wet season length as the time between climatological rainy season onset and withdrawal. The amount of precipitation during the wet season in the Tropics and subtropics is substantial relative to the annual precipitation total in most regions (Fig. 5). Over most of the land regions the contribution of wet season rainfall to the annual total is 60% to over 80%, except over North and Central America where the wet season contribution is generally near 50% of the annual total. Note, however, that the 80%–90% of the annual rainfall typically falls over the monsoon season in the southwestern United States. The length of the wet season is shortest in Central and North America, interior India, northern Australia, and over the northern fringe of the tropical northern Africa region. In contrast, the longest wet seasons are observed over near-equatorial Africa and interior Brazil.

There is little correlation between onset and subsequent seasonal rainfall accumulation. This observation is consistent with the observation of Marengo et al. (2001), who documented similar results over South America, and with Bansod et al. (1991), who concluded similar findings over the Indian subcontinent. There is also scant and spatially scattered correlation between withdrawal date and seasonal rainfall. More surprisingly, however, is that there is little correlation between accumulated rainfall and rainy season length as well.

Although there is little widespread correlation between wet season onset and subsequent wet season rainfall accumulation over all of the major monsoon regions, one must consider that the correlation statistic quantifies the variations between onset and precipitation accumulation over the entire time series. And while there is little correspondence between these variables over the entire record, there does appear to be some association between date of onset and seasonal rainfall accumulation for the extreme cases. For example, when the mean seasonal precipitation is compared between a composite of the precipitation during the 5 yr of earliest onset with the 5 yr of latest onset during 1979–99 (top and bottom quartiles of the distribution of onsets), the results suggest that years with early wet season onset receive more rainfall compared to late onset years (Fig. 6). This observation is most apparent over the Americas (except in west-central Brazil), the northern Africa monsoon region, and most of Asia. Over the Australasian region, the association between wet season rainfall amount and early compared to late wet season onset is considerably weaker and more localized.

d. Variations in the frequency of light and heavy precipitation events

For the purpose of the following discussion, we define light and heavy events as pentads with rainfall accumulations that rank in the upper and lower one-third of the distribution, respectively, for all rainy season pentads over the 21-yr period (1979–99). Similarly, we refer to ''poor'' and ''abundant'' wet seasons as those with accumulated precipitation during

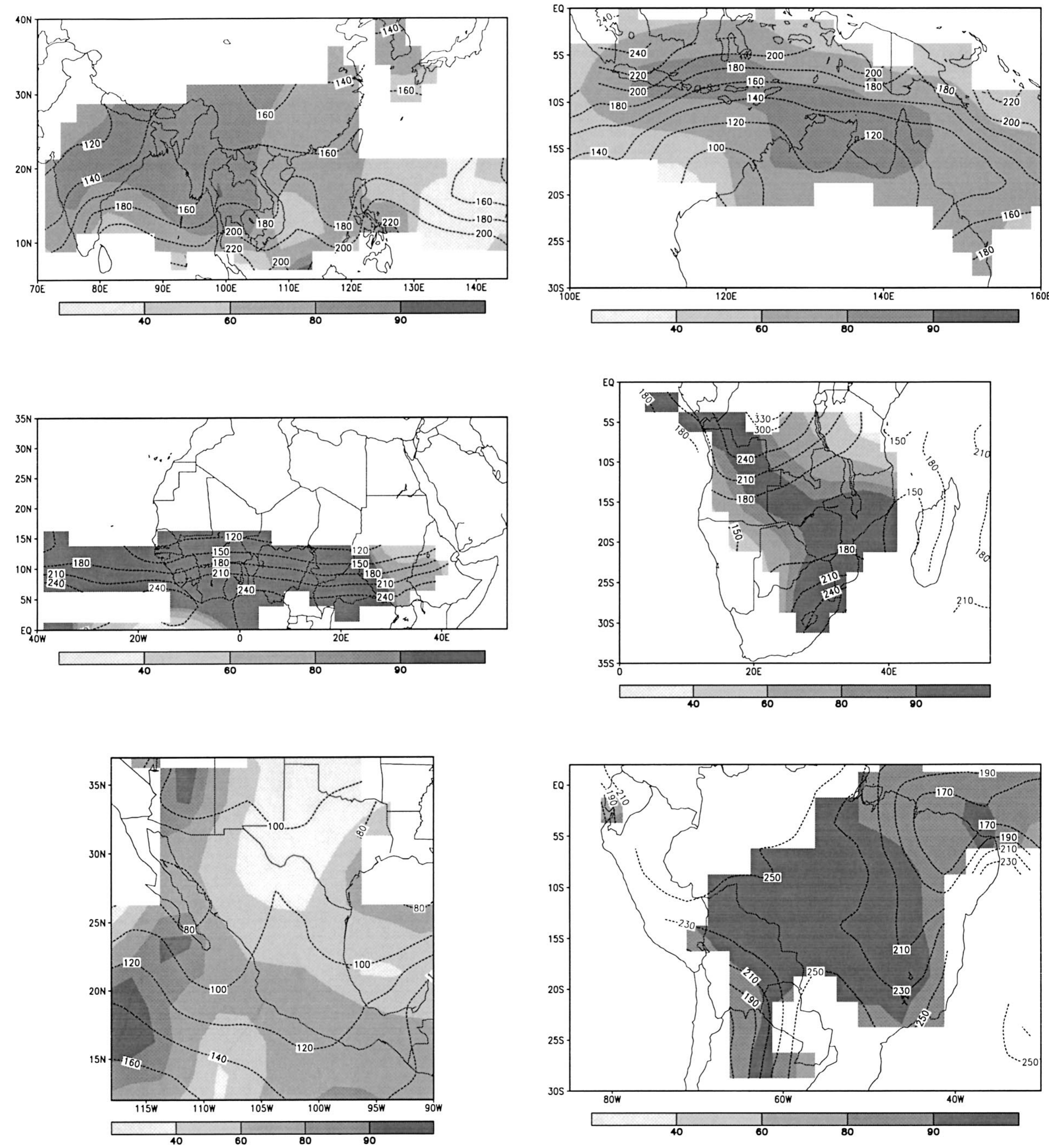

FIG. 5. Mean wet season length in days (contours) and the percentage of rainfall during the wet season to the annual total rainfall (shading) over the period 1979–99 from the GPCP pentad dataset.

the wet season that rank in the upper one-third (rainiest seven seasons) and lower one-third (driest seven seasons), respectively. Using these definitions, we examine the difference in the number of heavy and light events that were observed in abundant and poor wet seasons. The pattern of differences in the number of heavy events (Fig. 7) during abundant wet seasons compared to poor ones is similar to the difference in accumulated precipitation between early and late onset years (Fig. 6). Note that there is a widespread and marked increase in the number of heavy events during abundant wet seasons over most of the monsoonal regions with the exception of the eastern half of the Australasian domain. There is a similar increase in

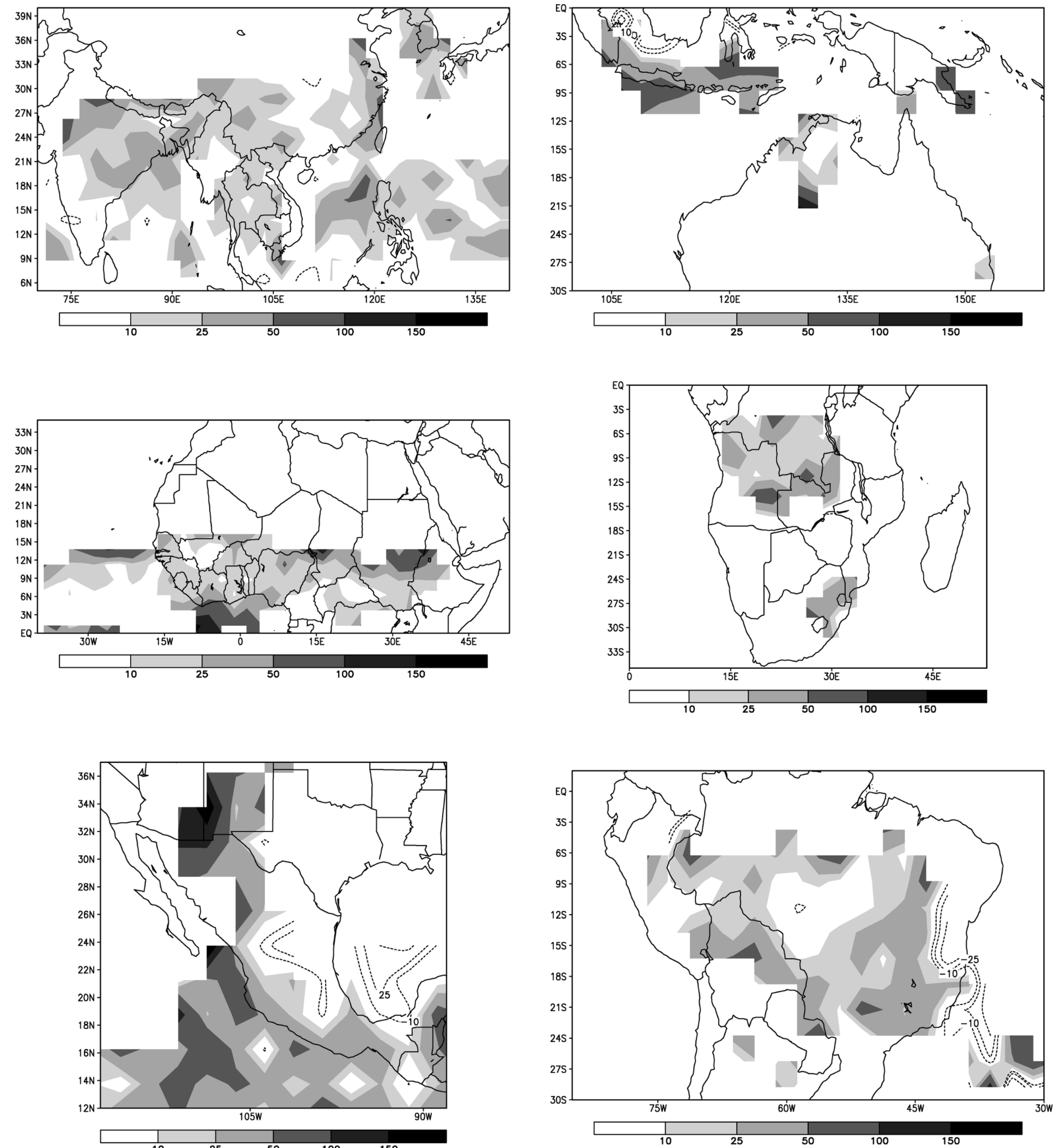

FIG. 6. Percentage difference in composite wet season precipitation between the five seasons with earliest wet season onset and the five with the latest onset over the 21-yr period 1979–99 from the GPCP pentad dataset. Shading (dashed lines) indicate more (less) wet season precipitation in earliest onset years compared to latest onset years.

light events as well over these regions (not shown), although the patterns are not as widespread as with the heavy events. Thus, while it is observed that more pentads with heavy rainfall occur during abundant wet seasons compared to poor ones, there are also simply more pentads with rainfall regardless of the intensity of the rainfall.

5. Rainy season precipitation variability associated with variations in the 250-hPa streamfunction

Mo and Kousky (1993) present evidence of a ''global mode'' of planetary-scale anomalies in the upper-tropospheric general circulation. This mode is identified by the first loading pattern of an empirical orthogonal

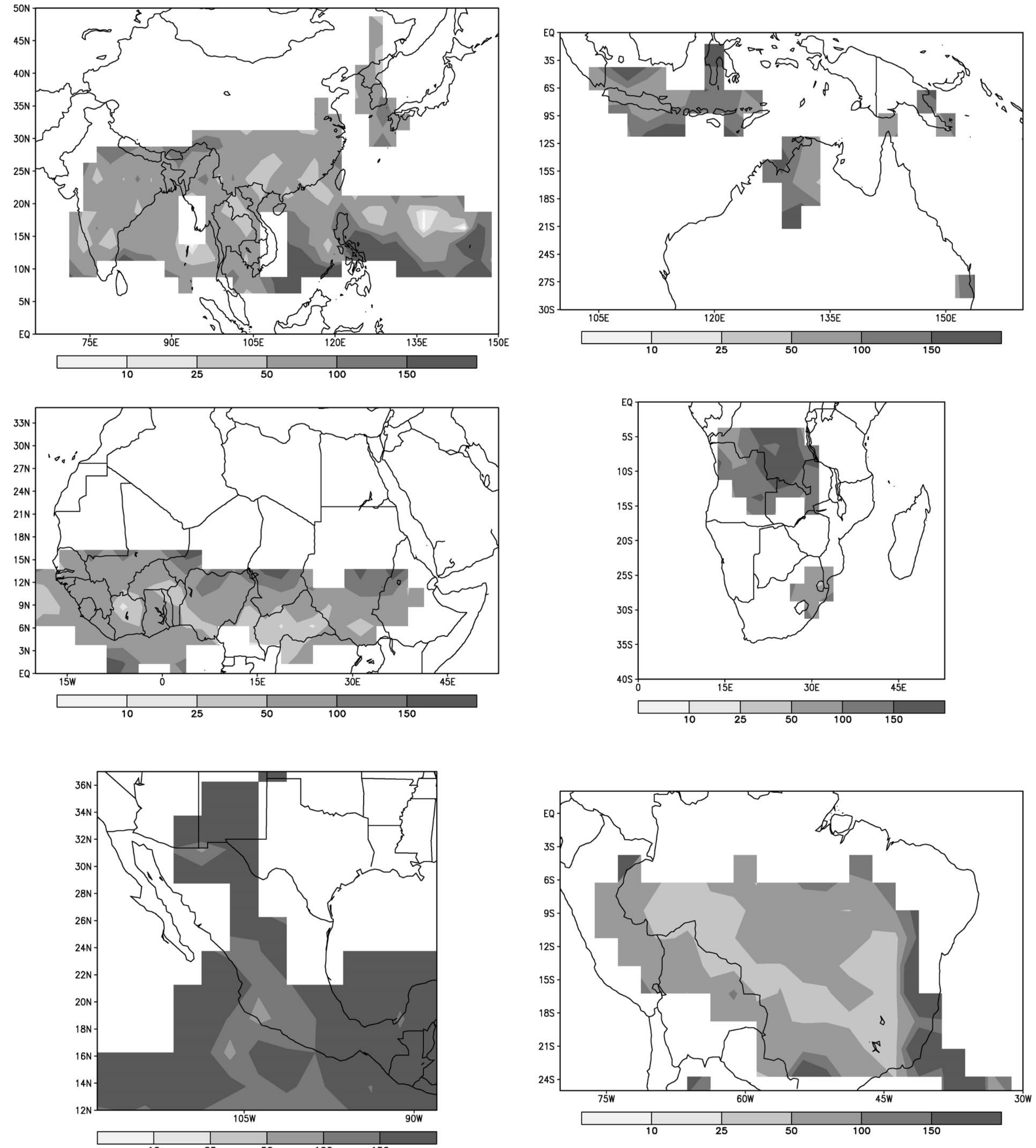

FIG. 7. Mean percentage difference in heavy events between wet seasons with abundant and poor rainfall over the period 1979–99 from the GPCP pentad dataset. Heavy (light) events are defined as pentad rainfall totals in the highest (lowest) third of the distribution of all wet season rainfall during the 21-yr period. Abundant (poor) wet seasons are those in which the rainfall accumulations over the wet season rank in the top (bottom) third of the historical distribution.

function analysis on 250-hPa streamfunction anomalies, which depicts a pattern of anomalies of opposite sign in the Northern and Southern Hemispheres. When the mode is active and positive anomalies occur in the summer hemisphere, the subtropical anticyclonic circulations are stronger than normal (and vice versa), which suggests an association between this mode and the strength of the global monsoon circulations. Bell et al. (2000) conclude that the phase of this mode is associated with the increased vigor of the anticyclonic circulations and is tied in part to the ENSO cycle. Many others have investigated the relationship between ENSO and variations in monsoon rainfall in India and Southeast Asia (Barnett 1984; Shukla and Paolino 1983; Meehl 1987, 1989; Webster and Yang 1992, to name a few). These studies prompted us to examine possible relationships between variations in wet season precipitation amount and the phase of this global mode.

Area-averaged rainfall was computed for each rainy season during 1979–99 over each of the major monsoon regions. The driest and wettest 25% of those seasons were determined for each region separately. We then composited the 200-hPa streamfunction anomalies for the years in which precipitation was in the driest and wettest 25% of the 1979–99 period. To ensure confidence that the years used in the composites are not associated with this global mode by random chance, we tested the significance of the composite years via a Monte Carlo approach. To do this, random selections of years were made and the resulting random composite values were compared at each grid location to the value of the original composites. This process was repeated 1000 times at each grid location and, if the original composite value exceeded the random year composite value 95% of the time (950 of the 1000 iterations), the original composite years were deemed to be significantly different from a random selection of years.

These composites reveal a strong association between this global mode and wet season precipitation in some, but not all, of the regions that we examined (Fig. 8). Recall that anticyclonic circulation anomalies are indicated by positive streamfunction anomalies in the Northern Hemisphere and negative streamfunction anomalies in the Southern Hemisphere. The strongest association is in the Australasia region, where all of the five driest of seasons occurred during seasons when the mode had negative anomalies in the Southern Hemisphere (anticyclonic circulation anomalies), while all of the wettest occurred in seasons when the mode was of the opposite sign. It is notable that of the five seasons that make up the composites for poor Australian wet seasons, four are seasons when active El Niño conditions were observed and the remainder is an ENSO-neutral year. Conversely, of the five years that make up the composites for abundant Australian wet seasons, four are La Niña years and the remainder is an ENSO-neutral year. Strong associations are also observed between this mode and abundant wet season precipitation in Asia and northern Africa, and with poor wet season precipitation in South America and India.

It is possible that the association between this circulation mode and wet season precipitation may be more robust in other regions as well than is indicated in this short record (21 yr) due to the effect of other aspects of variability within the climate system that are magnified by the short record. As an example, although there appears to be scant association between poor wet season rainfall over India and the global mode during the 1979–99 period, we composited the 200-hPa streamfunction anomalies for the driest 12 seasons (25% driest) during 1949–97 based on rain gauge data and a very strong association with the global mode is indicated. Of course the reverse may also be true, that is, that regions with apparently robust associations may be less robust because it is possible that the 21-yr period over which the results in this paper are presented may have been a fairly benign period for other naturally occurring climate variations.

6. Summary

We have demonstrated one aspect of the utility of the pentad GPCP precipitation dataset and in the process have described some basic behavior of several low-latitude regions that experience a single, pronounced wet season. To describe this behavior, we devised a procedure with which we were able to determine objectively the onset and withdrawal of wet season precipitation. This procedure, combined with the relatively fine temporal scale of the data, allowed us to quantify objectively the wet season onset, withdrawal, and length for individual years and the interannual variability among them. The temporal resolution of the pentad GPCP dataset also permitted us to analyze the frequency of light and heavy rainfall events. By using these results in conjunction with atmospheric data from the NCEP–NCAR reanalysis dataset, we have shown possible associations between the variability of global-scale upper-tropospheric circulation features and wet season rainfall accumulation over several regions of the globe.

The following is a summary of our main conclusions:

1) Wet season onset and withdrawal are most spatially uniform over India, North America, the Australasian region, and Africa, and the most complex over Asia and South America.
2) Substantially more interannual variability exists for withdrawal (10 to >40 days) compared to onset (<10 to 30 days). The largest interannual variability in both onset and withdrawal date occurs in Australasia and North America. The smallest interannual variability in both onset and withdrawal date occurs over northern tropical Africa.
3) Although the correlation between onset and seasonal rainfall accumulation is ubiquitously low, there does appear to be an association between these quantities when only the seasons of earliest and latest onset are contrasted.
4) Wet season length varies substantially over the earth, ranging from about 100 days over Mexico to over 250 days over much of near-equatorial Africa and central Brazil.
5) During abundant wet seasons, 10%–50% more pentads with heavy rainfall are observed compared to the number during poor wet seasons. More light

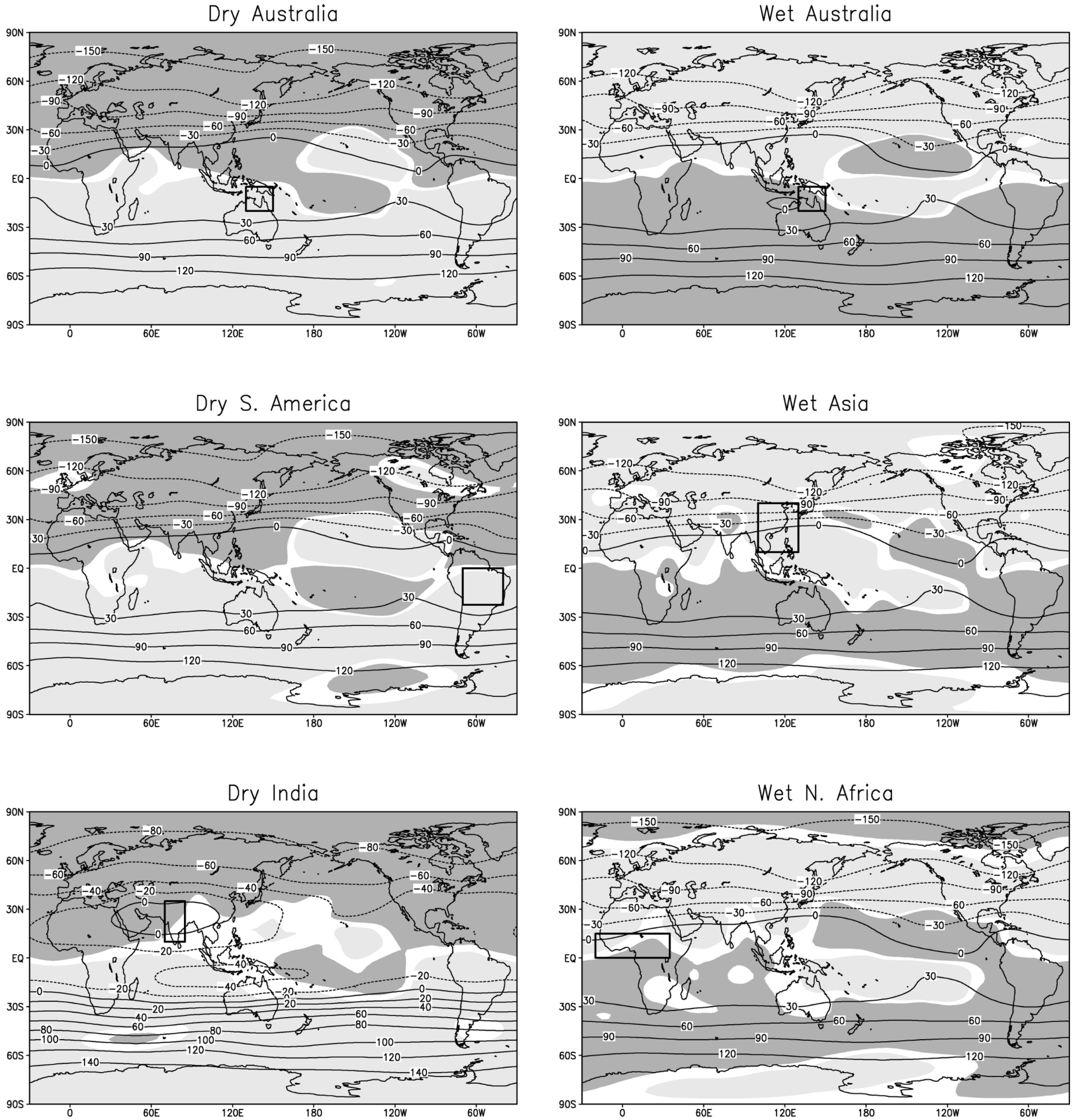

FIG. 8. Composites of 200-hPa streamfunction (contours) and anomaly (shading). Units are 10^{-6} m^2 s^{-1}. Anticyclonic circulation anomalies are indicated by positive streamfunction anomalies (light shading) in the Northern Hemisphere and by negative streamfunction anomalies (dark shading) in the Southern Hemisphere. Composite years for each plot are those years with the wet season rainfall totals that rank in the driest or wettest 25% of the historical record over the regions described in the titles of each plot. Rectangles on plots denote areas over which precipitation was averaged to determine the wettest and driest seasons. For each region except India, the historical record is 1979–99. For India, the historical record spans the years 1949–99.

events are observed as well during abundant wet seasons.

6) There appear to be strong associations between a so-called global mode and seasonal rainfall in several regions. This mode is characterized by anomalies in the 200-hPa streamfunction of opposite sign in the Northern and Southern hemispheres and reflect the strength of the subtropical anticyclonic circulations, the strength of which is associated with the relative monsoon strength. For example, the five driest and wettest wet seasons over Australia during the 1979–99 period occurred concurrently when opposite phases of this mode were observed. Specifically, the five most abundant rainy seasons occurred there when

the upper-level anticyclonic circulations were stronger than normal and the five poorest wet seasons occurred when these circulations were weaker than normal.

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