A Hydrological Definition of Indian Monsoon Onset and Withdrawal

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ABSTRACT

A diagnostic criterion that retrospectively assesses the onset and withdrawal dates of the Indian monsoon is derived from variability in the large-scale hydrologic cycle. The method is proposed as an improved means with which to understand interannual variability in the monsoon transitions as compared to criteria that rely heavily on rainfall variability over limited spatial domains (e.g., individual Indian districts). The hydrologic cycle is chosen as a key physical basis for monitoring the monsoon due to the essential roles played by zonal and meridional gradients in water vapor, clouds, and rainfall in driving the large-scale monsoon circulation. Moreover, as rainfall is greater than evaporation in wet monsoonal areas, lateral transports of water vapor are required for the existence of monsoonal rains. To diagnose onset and withdrawal, vertically integrated moisture transport (VIMT) is therefore used instead of rainfall, which over the large scale is often poorly measured and modeled. In contrast to rainfall, VIMT is generally well modeled and observed, and its variability, particularly over the Arabian Sea, is substantial during both monsoon onset and withdrawal. An index, named the hydrologic onset and withdrawal index (HOWI), is thus formed from those regions where VIMT variability is pronounced at the beginning and end of the monsoon season. The HOWI offers several advantages as the index is based on fields that are better modeled and measured than rainfall, and the index is indicative of the transition in the large-scale monsoon circulation rather than being highly sensitive to synoptic variability and the spatial complexity of the monsoon transitions. The HOWI is shown to be both robust to bogus monsoon onsets and reflective of the timing, rather than the spatial character, of the transitions.

Analysis of interannual variability in monsoon onset and withdrawal dates based on the HOWI reveals robust associations that are weak and insignificant when assessed using other onset criteria. For example, the associations between total June–July–August–September (JJAS) rainfall and both monsoon onset and withdrawal are weak (correlations are weaker than −0.11) when onset dates from the Indian Meteorological Department (IMD) or other objective methods are considered. However, the HOWI criterion shows strong correlations between total JJAS rainfall and both onset (0.30) and withdrawal (−0.49). Thus, the length of the monsoon season is shown to be strongly related to its overall strength. In addition, while the correlation between IMD onset date and Niño-3 SST is insignificant, the correlation based on HOWI is 0.41. The associations between HOWI and both ENSO and the overall monsoon season exceed significance at the 99% confidence level. Moreover, the associations are shown to be robust to the scale of the region selected in compiling the HOWI. It is speculated that the influence of synoptic variability and the spatially variable nature of the monsoon transitions mask, in part, the existence of the climate associations that are revealed by the HOWI.

1. Introduction

The onset and withdrawal of the broadscale Asian monsoon occur in many stages and represent significant transitions in the large-scale atmospheric and ocean circulations in the Indo–Pacific region (e.g., Rao 1976; Murakami and Nakazawa 1985; Lau et al. 1998; Hsu et al. 1999; Wu and Zhang 1998). While there exist no widely accepted definitions of these monsoon transitions, at the surface the onset is recognized as a rapid, substantial, and sustained increase in rainfall over a large scale while the withdrawal marks the return to dry, quiescent conditions. Typically, rainfall amounts over India increase from below 5 to over 15 mm day^{-1} during onset (Anathakrishnan and Soman 1988, hereafter AS; Soman and Kumar 1993). It is also known that the onset experiences spatial coherency over a large scale. Figure 1 shows isopleths of the average dates of the commencement of the monsoon rains (Ramage 1971). The pattern of onset in Fig. 1 is obtained by averaging rainfall patterns over several decades and during any single year the initiation of rainfall at a single location can be very different from the climatological pattern. In general, however, the first rains of the monsoon occur over Burma and Thailand in mid May and extend subsequently to the northwest, so that by mid June, rains have advanced over most of India and Pakistan. Near India, the onset occurs initially across the peninsula's southern tip in early June, progressing northwestward across most of the country in the following

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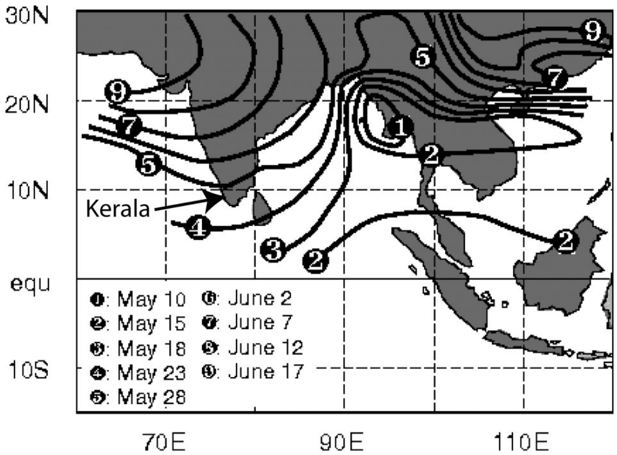

FIG. 1. Climatological dates of the onset of the south Asian summer monsoon, constructed using data from data in Ramage (1971), Das (1987), and Hastenrath (1994).

month. The northward progression of the monsoon onset is symptomatic of a large-scale transition of deep convection from the equatorial to continental regions (e.g., Rao 1976; Sikka and Gadgil 1980; Webster 1983; Webster et al. 1998). Methods that determine even the mean onset dates, such as in Fig. 1, can show large disagreements however, due to the scarcity of, and inaccuracies in, existing rainfall climatologies (Tao and Chen 1987; Tanaka 1992; Lau and Yang 1997; Wang and Lintto 2002). Moreover, measurements in and around the centers of strongest monsoonal rainfall over ocean are particularly scarce (Wang and Lintto 2002).

The seasonal monsoon transitions can unfold in a variety of ways with abrupt, gradual, or multiple transitions occurring in various years that together encompass different timings and spatial patterns (e.g., Flatau et al. 2001; Fieux and Stommel 1977; Pearce and Mohanty 1984; Tanaka 1992). Though, at the surface, the monsoon transitions are first revealed by variability in rainfall, a variety of dynamic and thermodynamic precursors are known to exist (e.g., Ananthakrishnan and Soman 1991; Murakami et al. 1986). Thus, in an effort to simplify the determination of the transitions amidst the complexity of the monsoon's large-scale evolution, rainfall variability at Kerala, India (Fig. 1), rather arbitrarily, is often used (e.g., AS; Ananthakrishnan et al. 1967). Based on Kerala rainfall, the mean onset date occurs near 1 June and varies with a standard deviation of 8–9 days from year to year while withdrawal occurs in early October. It is not known, however, whether the choice of rainfall in a single Indian region, which is on the order of 200 km in breadth, is adequate to characterize interannual variability in the monsoon transitions, which are of planetary scale and experience variability in their spatial structure from year to year.

The suddenness of rainfall fluctuations during the monsoon's transitions is well established (e.g., Ramage 1971; Rao 1976; AS; Wang and Xu 1997; Wang and LinHo 2002). In Kerala, the rapid, intense, and sustained transition signaled by the onset is clear as, on average, rainfall increases from near 5 to over 20 mm day^{-1} in less than 5 days and is sustained for almost 3 months (AS). The rapid transition results, in part, from instabilities that develop in the ocean–atmosphere system during springtime. However, traditional methods of defining onset also guarantee a marked increase in rainfall. While these methods assume that variability in rainfall at Kerala during June is dictated by the monsoon transition, the relative importance of local synoptic variability, which may or may not be related to the monsoon, and the climate-scale transition marking the monsoon onset is not known (e.g., Rao 1976; Webster et al. 1998).

The withdrawal of the monsoon is more gradual than its onset and is characterized by the reduction in rainfall over India, the decay of the anticyclonic circulation that is established over the Tibetan Plateau during the monsoon, and the reappearance of the upper-level westerly jet stream south of the Himalayas [e.g., Dey 1970; India Meteorological Department (IMD) 1972]. As during onset, the monsoon's major convective zones undergo a meridional migration during withdrawal that results in a northerly migration of deep convection associated with large-scale interactions between thermal, dynamic, and hydrologic processes. As during onset, variability in rainfall at Kerala during the monsoon's withdrawal results from both local synoptic variability and the monsoon transition.

The monsoon transitions occur due to large-scale interactions between surface heating and atmospheric dynamic, thermal, and hydrologic processes (Takagi et al. 2000; Hsu et al. 1999; Kumar et al. 1997; Ueda and Yasunari 1998; Wu and Zhang 1998; Webster 1983). However, the extent to which rainfall at Kerala during these transitions is determined by synoptic variability unrelated to the monsoon transitions is not well established. Moreover, given the relatively small scale of Kerala ($<$200 km in breadth), sensitivity of any onset or withdrawal declaration based solely on the district's rainfall to spatial intricacies in the monsoon transitions is also likely to be large.

Though the decision to base declaration of monsoon onset and withdrawal on Kerala rainfall is largely arbitrary—it is on average the first colonized region to experience the advance of monsoon rains—there are several motivations to diagnose the transitions by district rainfall. First, the availability of surface rainfall observations across much of India, that have been made since the late nineteenth century, allows for widespread assessment of the monsoon over an extended climatology. Few observations of upper-air conditions exist across such an extended period. Moreover, among the meteorological fields that signal the monsoon transitions, rainfall has perhaps the largest impact on human activities. As agriculture in an individual district is impacted by synoptic variability in rainfall and not necessarily the large-scale state of the monsoon system, a local definition of the transitions is of clear practical significance.

Despite the motivations for using Kerala rainfall as a basis for monsoon assessments, there also exist a number of challenges posed by its use. For example, precipitation is among the most difficult fields to monitor, involving complex spatial and temporal gradients. Though the complexity of rainfall does not negate its importance, it does raise questions regarding the ability of rainfall over a single district to diagnose adequately the planetary-scale monsoon (Soman and Kumar 1993; Joseph et al. 1994). For example, rainfall within a district is highly susceptible to ''false'' or ''bogus'' monsoon onsets, which are associated with propagating tropical intraseasonal disturbances unrelated to the monsoon onset (e.g., Flatau et al. 2001). The disturbances are characterized by an enhancement of convection and westerly surface winds similar to the monsoon onset but occurring over a smaller scale and lasting a week or less. Often, bogus onsets are followed immediately by extended periods of weak winds and clear skies that result in heat waves and droughts in India. These droughts can cause considerable economic and agricultural damage when incorrectly predicted, as crops planted in anticipation of the monsoon are likely to fail as a result of the bogus onset. As bogus onsets can predate the actual onset by up to several weeks, it is also important for any retrospective onset determination to be insensitive to their occurrence. The fact that rainfall over a limited domain may not necessarily reflect the broad-scale monsoon is also recognized by the IMD, which thus involves subjective consideration of the large-scale circulation in its official declaration of monsoon transitions. While the inclusion of subjective assessments may ameliorate some of the challenges posed by Kerala's limited domain, it also introduces a new source of potential error—subjectivity in the onset declaration. Variability in the IMD's transition dates can thus stem from the subjective nature of the IMD's decision, the susceptibility of objective methods to synoptic variability, and the spatially variable nature of the monsoon transitions.

Existing onset identifications

While methods that identify the monsoon's withdrawal date are few, a number of techniques have been developed to identify monsoon onset. Some methods focus on understanding the climatological mean date of onset by region (e.g., Tao and Chen 1987; Tanaka 1992; Lau and Yang 1997; Wang and Lintto 2002). While these assessments are important, they do not offer insight into the interannual variability of the monsoon transitions and their relationships with other climate features such as ENSO.

Two methods that identify the interannual fluctuations of onset date include the objective method developed by AS and the more subjective declarations of the IMD.

TABLE 1. Correlation of existing monsoon onset indices with all India rainfall and JJAS Niño-3 SST. All correlations fail to show significance at the 95% confidence level.

Index (mean date: std dev)	All India rainfall	Niño-3 SST
IMD (2 Jun: 7.5)	−0.10	0.17
South Kerala (30 May: 8.6)	−0.09	0.16
North Kerala (1 Jun: 8.5)	−0.11	0.23

Ananthakrishnan and Soman show the potentially large disagreements that can arise in comparing objective and subjective assessments of onset. For example, in 1969 IMD's declaration of onset on 17 May disagrees with the objective classification of AS by 8 days. In 1959, the disagreement is 19 days and in 1943 and 1932 the disagreements are 17 and 19 days, respectively. Moreover, other years, such as 1979 and 1995, are associated with bogus onsets that objective methods can misdiagnose by up to three weeks (Flatau et al. 2001). Any studies of onset and its variability must be able to resolve accurately the onset with a precision that is small relative to interannual variations while at the same time being resilient to the occurrence of bogus monsoon onsets. From AS it is clear that either IMD estimates or objective criterion applied to district rainfall, or both, are unable to report monsoon onset to the required precision in some years.

Though speculation exists that the onset may be related to other aspects of climate such as the overall strength of the monsoon season and ENSO (e.g., Joseph et al. 1994), the relationships between onset dates based on existing criteria and other climate features are weak. Table 1 summarizes statistics regarding the onset dates from the subjective method of the IMD, objective methods over North (NK) and South Kerala (SK), and their correlation with both the overall strength of the monsoon season, as judged by June–July–August–September (JJAS) all India rainfall, and ENSO [as diagnosed from reconstructed Reynolds JJAS SST in the Niño-3 region (5°S–5°N, 150°–90°W)]. On average, onset occurs on 30 May, 1 June, and 2 June for SK, NK, and the IMD, respectively, with a standard deviation of 8–9 days from year to year. The onset shows little or no association with monsoon strength, as the correlations are −0.10 for IMD, −0.09 for NK, and −0.11 for SK identifications with statistical significance not greater than the 90% confidence level. The simultaneous associations between onset and Niño-3 SST are also weak with 0.17, 0.16, and 0.23 for IMD, SK, and NK, respectively. Thus, no significant correlations can be found between onset, JJAS rainfall, and ENSO and less than 6% of the variance in the onset can be explained by variability in either climate feature. As significant associations between the onset, as defined by Kerala rainfall, and other climate features are few, one is faced with many questions. Is it probable that a major climate phenomenon, such as the monsoon onset, which relies on large-scale (>3000 km in breadth) interactions between heat, moisture, clouds, and winds, has no significant associations with either ENSO or the monsoon season itself? On the other hand, is it possible that the associations, if existing in nature, are masked by the inadequate sampling of poorly measured parameters (e.g., rainfall) used by existing criteria? Are the district-scale indices currently used optimal for assessing the onset of the planetary-scale monsoon or is synoptic variability, subjectivity in the indices, and undersampling of the spatially complex monsoon onsets masking important relationships that exist in nature?

There are several motivations to develop a diagnostic of the monsoon onset and withdrawal that is reflective of the transition in the large-scale circulation rather than rainfall over a single Indian district. Most importantly, such an index may reveal important predictive relationships between the monsoon and other major climate features. For example, such a diagnostic may assist in clarifying the accuracy of the large-scale teleconnections summarized in Table 1. Moreover, with the promise of improved forecasts of ENSO (e.g., Penland and Magorian 1993; Chen et al. 1995), mechanisms that couple the monsoon with the tropical Pacific Ocean have particular relevance to monsoon forecasting. The ability to accurately predict an early or late monsoon onset or withdrawal is of substantial economic consequence, even if such a forecast can only be applied broadly to the Indian peninsula. To date however, there has been no objective analysis to suggest strong linkages between the monsoon transitions, total Indian rainfall, and ENSO. In order to clarify the relationships, this study develops an objective large-scale determination of the monsoon onset and withdrawal that reflects the transition in well-measured parameters of the monsoon hydrologic cycle. The associations between the onset and withdrawal dates and the overall strength of the monsoon and ENSO are then assessed.

2. Method and data

The hydrological cycle can be most generally described by the vertically integrated moisture transport (VIMT) into and out of a region, and the precipitation (P), evaporation (E), and precipitable water (PW) within the region. Vertically integrated moisture transport is defined as

$$\mathrm{VIMT} = \int_{\mathrm{surface}}^{300\ \mathrm{mb}} q\mathbf{U}\, dp,$$

where q is the specific humidity and $\mathbf{U}$ is the wind vector. Above 300 mb, specific humidity amounts are poorly known and are therefore not part of the reanalysis (Kalnay et al. 1996). However, above 300 mb specific humidity in the Tropics is at least two orders of magnitude smaller than near the surface, and moisture transports are therefore of negligible influence to the calculation of total VIMT.

The National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses from 1948 through the present time (Kalnay et al. 1996; Kistler et al. 2001) are used to estimate variability in the hydrologic cycle. The reanalyses incorporate global rawinsonde data, the Comprehensive Ocean–Atmosphere Data Set (COADS) surface marine data, and surface land synoptic data throughout the study's analysis period (1948–present). Despite a lack of rawinsonde data over the ocean, many observations of the hydrologic are incorporated into the assimilation processes in these regions. Satellite sounder data, available from the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) and the Satellite Infrared Radiation Spectrometer (SIRS) sounders through most of the later part of the analysis period (1979–present), provides humidity and temperature estimates over both ocean and land regions. Moreover, cloud-tracked winds and oceanic reports of surface pressure, temperature, horizontal wind, and specific humidity are also included in the assimilation process. As the reanalysis model also exerts an influence on the final output fields, outputs are categorized by type. For type A fields, such as the rotational wind and upper-air temperatures, the output is strongly influenced by assimilated data and considered the most reliable. However, for type B fields the influence of both observations and the model during the assimilation processes can be important. Humidity and divergent wind fields are examples of type B fields. Fields, such as rainfall and evaporation, that are purely model derived subject to the constraints imposed by assimilated observations, are categorized as type C. Thus, total VIMT is calculated from specific humidity (type B) and wind (type A/B) fields at each pressure level and 6-h forecast interval. While the fields are importantly based on both satellite and in situ data, there exists some concern that the reanalysis model has also influenced the fields. In the monsoon domain, however, errors induced by the model are small as Fasullo and Webster (2002) show that reanalysis estimates of humidity agree closely with satellite retrievals from the National Aeronautics and Space Administration (NASA) Water Vapor Project (NVAP) over India and the northern Indian Ocean.

Niño-3 SST is taken from the Global Sea Ice and Sea Surface Temperature dataset (GISST; Rayner et al. 1996), Reynolds SST (Reynolds and Smith 1994), and reconstructed Reynolds SST (Smith et al. 1996) anomalies in the Niño-3 region averaged over the months of JJAS. For the most recent decades (1981–2001) Reynolds SST is used while from 1950 to 1981, reconstructed Reynolds SST is used and before 1950, GISST data is used.

3. The seasonal mean monsoon and the evolution of monsoon onset

There are many motivations for using the hydrologic cycle as a basis for determining the monsoon onset.

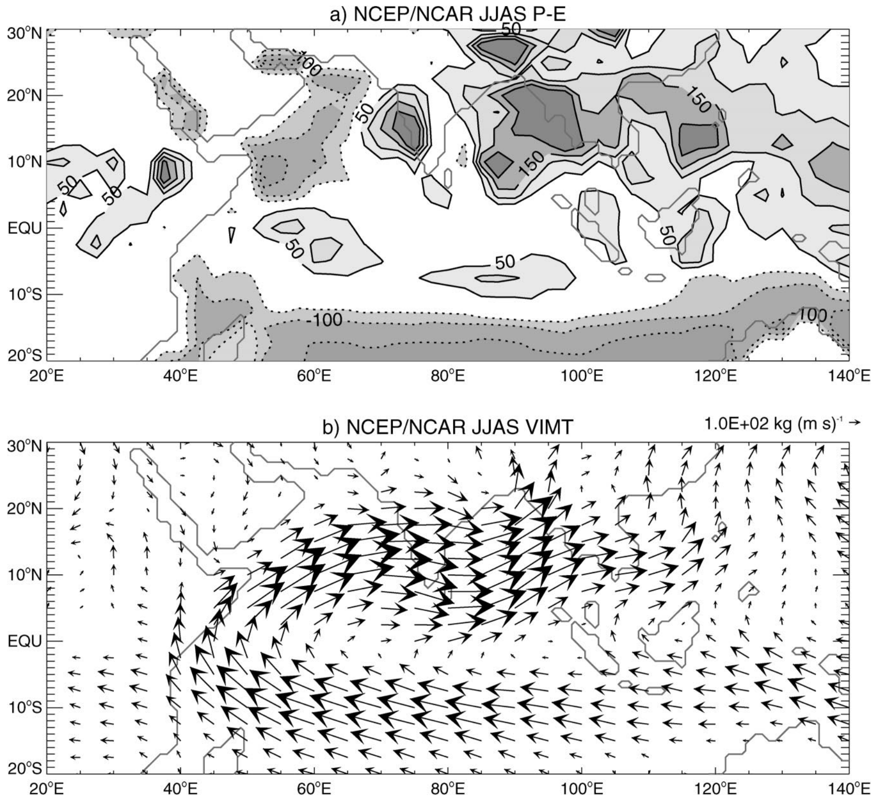

FIG. 2. Seasonal (JJAS) mean (a) $P - E$ and (b) VIMT based on the NCEP–NCAR reanalysis from 1948 to 2000.

First, spatial gradients in water vapor, clouds, and rainfall contribute substantially to both the seasonal mean and interannual variation of the latent and radiative heating gradients that drive the monsoon circulation (e.g., Webster 1994; Webster et al. 1998; Fasullo and Webster 2002). Hydrologic fields, such as VIMT, are therefore linked directly to the basic monsoon forcings. Aspects of climatological mean monsoon hydrologic cycle, including $P - E$ and VIMT are shown in Fig. 2. The centers of deep convection near western India, the Bay of Bengal, and Southeast Asia where moisture convergence is strong ($P \gg E$) are supplied with moisture by transports in the monsoon gyre that originate from the divergent ($P - E \ll 0$) regions of the Southern Hemisphere and Arabian Sea. Because evaporation in the Indian region during the summer monsoon is small as compared to precipitation, moisture divergence in and moisture transport from remote regions is key to the initiation and maintenance of the heating that drives the monsoon. The monsoon's existence is therefore tied to hydrologic processes in the Arabian Sea and Southern Hemisphere. It should be noted that the spatial scales of the regions of both moisture convergence and divergence in the monsoon domain are extremely large, covering several million square kilometers while Kerala covers less than 10^5 km^2. Moreover, while the strongest regions of monsoonal moisture convergence exist over the ocean, existing onset definitions are based on rainfall over land.

4. Time–space characteristics of monsoon onset and withdrawal

Figure 3a shows the climatological mean (1948–2000) difference in VIMT and $P - E$ before (18–24 May) and after (8–14 June) the mean 1 June onset. The same fields are also shown in Fig. 3b for dates corresponding to monsoon withdrawal (e.g., Rao 1976). The largest 50 difference vectors that transport moisture into India during onset are highlighted to show where variability in the monsoon-related VIMT is largest. In addition to contributing to moisture convergence over India, the eastward VIMT vectors are responsible for transporting moisture toward the major convective centers of the monsoon from the divergent regions of the Arabian Sea and southern Indian Ocean (Fig. 2). Enhanced moisture convergence, as judged from $P - E$ fields, is both collocated with the eastern portion of the largest VIMT differences, and located downstream in the Bay of Bengal. According to the reanalysis, Kerala is located approximately between areas that experience enhanced [$\Delta(P - E) > 0$] and reduced [$\Delta(P - E) < 0$] moisture convergence during monsoon onset and its location does not therefore appear to be ideal for iden-

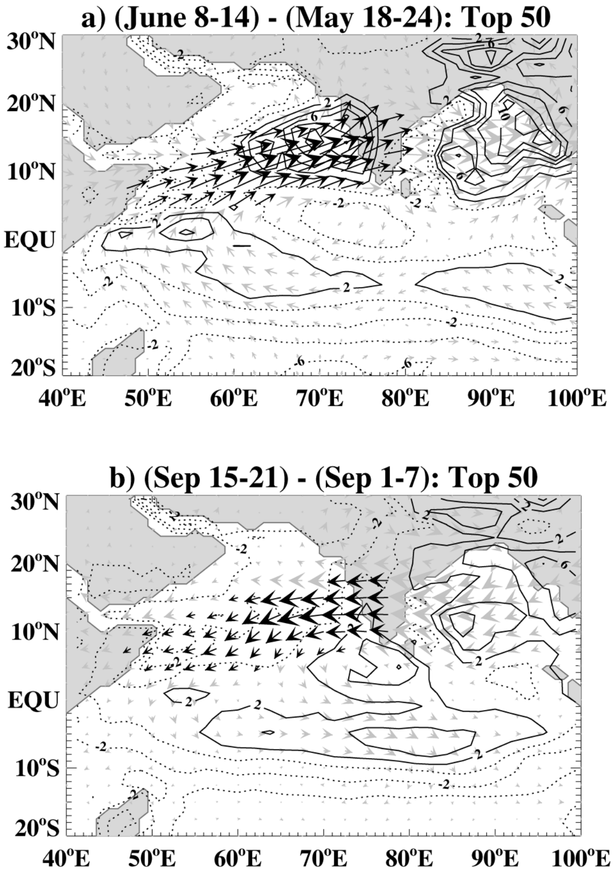

FIG. 3. The climatological mean difference in VIMT (vectors) and $P - E$ (contours) (a) after (7–15 Jun) and before (18–24 May) mean onset date of 1 Jun, and (b) after (15–22 Sep) and before (1–7 Sep) monsoon withdrawal based on fields from the NCEP–NCAR reanalysis. The 50 largest difference vectors, on which the HOWI is based, are bold.

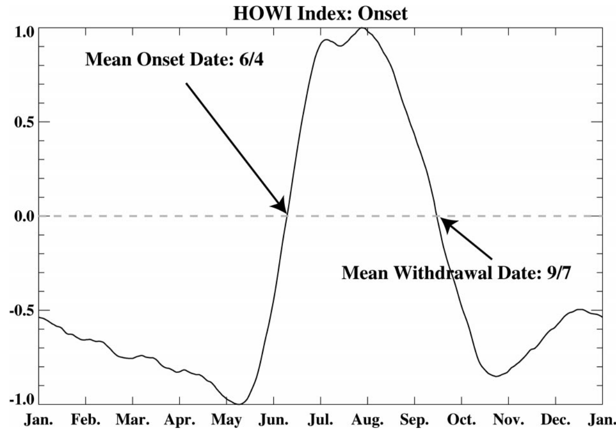

FIG. 4. Seasonal cycle of the HOWI.

tifying the center of convective enhancement associated with monsoon onset, which is located offshore. This finding needs to be viewed with caution however given the model influence on the reanalysis rainfall and evaporation fields already discussed.

During withdrawal (Fig. 3b), the southeastern progression of the decay of convection associated with the monsoon's retreat (e.g., Rao 1976) can be inferred from the reduction of moisture convergence [$\Delta(P - E) < 0$] over Pakistan and most of India. VIMT differences show a simultaneous reduction in westerly VIMT into India and the Bay of Bengal. A weakening of the large-scale monsoon hydrologic cycle and a return of equatorial moisture convergence is also apparent during this time.

5. Creation of a monsoon index based on the hydrologic cycle

There are several requirements for any onset and withdrawal criterion. The criterion should be

- associated with the establishment of the large-scale processes that drive the monsoon circulation;
- relatively insensitive to individual synoptic disturbances, bogus monsoon onsets, and active–break transitions that occur within the monsoon season;
- based on fields that have been well observed over an extended period so that the method can be employed over an extended climatology;
- based on fields that experience large and rapid variability during the monsoon onset and withdrawal.

To meet the above requirements, a time series of the mean VIMT in the highlighted region of Fig. 3a is chosen as a basis for the hydrologic onset and withdrawal index (HOWI). It offers the opportunity to track the evolution of monsoon hydrology while using the large-scale and relatively well-measured parameters of winds and humidity that exist over an extended time period through the 50-yr NCEP–NCAR Reanalysis project. Other reanalysis projects, such as the 40-Year European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis project (Gibson et al. 1997), will further contribute to the available data record with which monsoon onset can be assessed with the HOWI.

Figure 4 shows the normalized time series of the annual cycle of VIMT averaged over the regions of particularly rapid VIMT fluctuations during monsoon onset (Fig. 3). The time series, χ, is normalized by the transformation:

$$\overline{\chi} = 2 \times \{[\chi - \min(\overline{X})]/[\max(\overline{X}) - \min(\overline{X})]\} - 1,$$

where $\overline{X}$ is the mean annual cycle and $\overline{\chi}$ is the normalized time series, such that the climatological annual cycle ranges from -1 to 1. Monsoon onset and withdrawal are defined by the times of year at which the index exceeds, and falls below, zero, respectively. The decision to use zero as a criterion for declaring onset, while subjective, is based on the goals of both developing resilience to bogus onsets and the monsoon's active-break cycle and drawing a symmetry between the winter and summer hemisphere seasons (sections 6c and

6d). Moreover, modest agreement exists between the climatological mean onset dates as declared by the IMD and the HOWI using this criterion (section 6a). Finally, as the goals of the current study are directed at resolving interannual variability in onset rather than determining the mean climatological onset, subjectivity in the choice of threshold does not greatly influence the study's findings.

Figure 4 confirms the large and rapid variability of HOWI during both monsoon onset and withdrawal. A 7-day running mean is applied to mask the remaining but small influence of synoptic variability on the index. Monsoon onset is then defined as the date at which the index becomes greater than zero and withdrawal is defined as the date at which the index falls below zero. It should be emphasized that the scale over which VIMT is averaged is very large ($\sim 4 \times 10^6$ km^2) relative to the scale of Kerala. Though the scale chosen in highlighting the difference vectors is subjective, 50 vectors are highlighted in Fig. 3a so as to be large relative to both synoptic variability and spatial intricacies in the monsoon onset, but small enough to capture the rapid large-scale variability associated with monsoon onset. Though radiosondes measurements above the Arabian Sea are few, humidity fields from the NCEP–NCAR reanalysis agree closely with fields from the NVAP as shown by Fasullo and Webster (2002). Sensitivity to the scale of this subjectively selected region has not been verified however and will be addressed in subsequent analysis.

As the fields used in the HOWI are large scale, the index is intended to be regional rather than local, reflecting the timing of the large-scale hydrologic cycle rather than rainfall at a single point, whose interannual variability may or may not be reflective of the monsoon. Nonetheless, the index does have a regional bias toward India, as the area chosen for tracking the hydrologic cycle lies directly upstream from the VIMT that supports monsoonal convection over India and the major convective center that lies on its western coast. As the region lies distantly upstream from the convective centers of east Asia and the Philippine Sea, and as low frequency variability in the major centers of deep convection can act independently (Wang and Fan 1999), the index is not intended to track variability in other monsoon regions. The capacity of this simple large-scale index to track monsoon onset and withdrawal in the Indian sector is now examined.

6. Performance of the HOWI

a. HOWI and established onset indices

The dates of monsoon onset and withdrawal as identified from HOWI from 1948 to 2000 are shown in the appendix. Table 2 shows the correlation between onset, as identified by HOWI, and conventional monsoon onset indices based on objective assessments of rainfall and the IMD's subjective determination. Table 2 suggests that, despite the different methodologies used, interannual variability in onset as determined by the various methods agree closely with correlations exceeding 0.70 and the 99% confidence level in all cases. Table 2 also shows that the indices share about 50% of their variance and thus suggests that about half of the variability in rainfall at Kerala may be due to synoptic-scale rather than climate-scale variability, a speculation that will be further bolstered by findings in section 7. Here it is found that, while sharing a modest degree of variability, the onset methodologies also contain substantive differences.

TABLE 2. Correlations between monsoon onset by the HOWI and existing methods. Correlations exceed significance at the 99% confidence level but the time series share only about 50% of their variance. Also shown in parentheses are the correlations based on alternative scale selections for the HOWI.

IMD	IMD	SK	NK
HOWI	0.74	0.71	0.70
(2×10^6 km^2)	(0.73)	(0.71)	(0.71)
(7×10^6 km^2)	(0.64)	(0.69)	(0.70)

To establish further the suitability of the HOWI, the degree to which the index is resilient to bogus monsoon onsets must first be investigated. Moreover, the impact of active-break monsoon transitions on the HOWI must be examined to see if the index incorrectly reports midseason monsoon withdrawals. The manner in which HOWI varies during two recent ENSO events is then investigated briefly.

b. Representativeness of the index

As the distribution of rainfall at monsoon onset is known to be spatially complex and variable, the decision to select a fixed region in sampling VIMT is initially questionable. Moreover, as HOWI is based on only one component of the hydrologic cycle, its ability to characterize rainfall variations is unclear. Does the HOWI correspond to the acceleration of the overall hydrologic cycle in India, or is the index merely a reflection of moisture transport? Additionally, are variations in monsoon transitions as reported by the HOWI due to temporal variability of VIMT toward the deep convective monsoon regions, or is a spatial redistribution of the moisture transport the cause of interannual variations in the index? It is noteworthy that concerns relating to the spatial variability of the monsoon transitions are also relevant to identification methods based on district rainfall.

To assess the ability of the HOWI to resolve meteorological fluctuations commonly associated with monsoon onset, Fig. 5 shows the composite change in rainfall and 850-mb winds between the week before and after onset for both the HOWI and IMD identification methods. Both onset definitions resolve, on average,

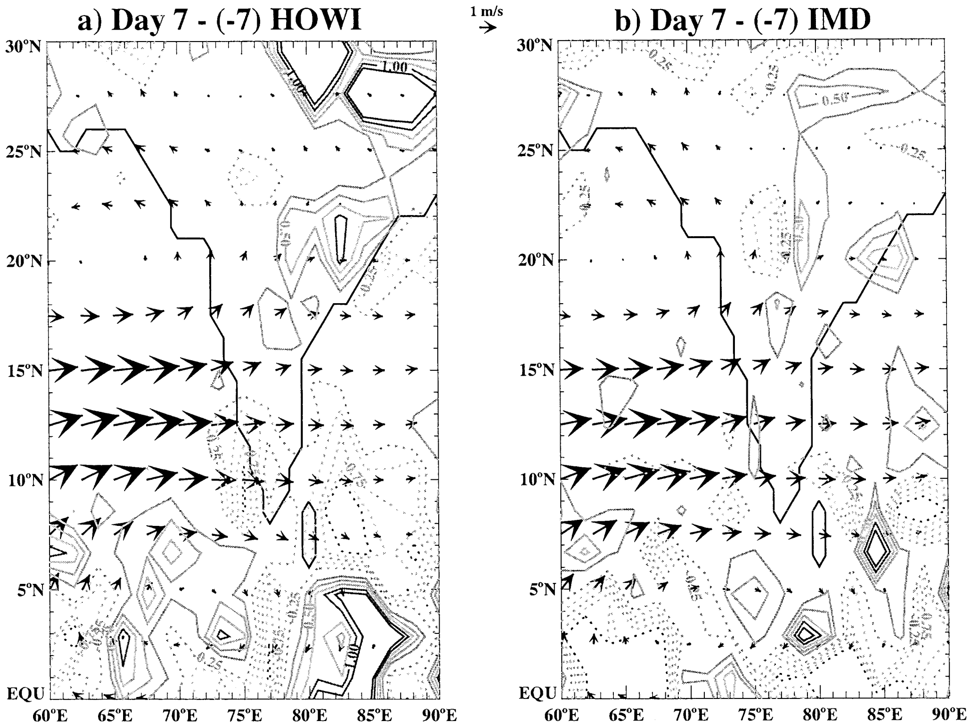

FIG. 5. Composite difference between 850-mb winds (vectors, m s^{-1}) and rainfall (contours, mm day^{-1}) between 7 days following and preceding monsoon onset based on (a) the HOWI and (b) the IMD. Stronger wind and rainfall anomalies associated with the southerly propagation of convective zones are identified by HOWI. Fields are from the NCEP–NCAR reanalysis from 1948 to 2001.

some important features of the onset such as the acceleration of winds over India and the Arabian Sea and the intensification and northward propagation of rainfall over the Indian peninsula (e.g., Rao 1976; Fieux and Stommel 1977). However, in the HOWI composite, variability in both winds and rainfall across onset are generally more pronounced than when using the IMD dates. Moreover, the zonally symmetric propagating structure of the onset is more clearly shown in the HOWI composite with well-defined zones of subsidence, in southern India, and precipitation, in northern India. Many of these features are weak or altogether absent from the IMD composite. Thus, while both methods capture some elements of the onset in the climatological composite, the onset identified by HOWI more clearly resolves many of the well-established onset features.

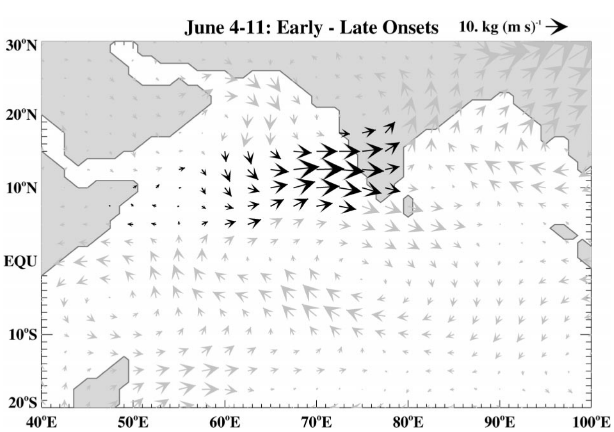

FIG. 6. Difference in VIMT from 4–11 Jun mean fields between the 10 earliest and latest monsoon onsets. The difference fields confirm the identification of a delayed onset by HOWI rather than merely its sensitivity to a redistribution of VIMT and rainfall fields.

To quantify the sensitivity of the HOWI to spatial complexity in onset, the VIMT difference field for the first week of the monsoon (4–11 June) between the 10 earliest and 10 latest monsoon onsets as identified by HOWI is shown in Fig. 6. The difference field in Fig. 6 shows that an early onset is generally associated with a net enhancement of VIMT into India in early June rather than merely a spatial redistribution of the VIMT flow, as the westerly VIMT difference in the monsoon gyre is everywhere positive. Thus, though the distribution of rainfall at monsoon onset can be complex and variable, other dynamically related aspects of the monsoon gyre, such as its VIMT, exhibit a more consistent spatial distribution from year to year—perhaps due to a locking between elements of the gyre (e.g., Somali jet) and geographical features (e.g., the Somali highlands; Krishnamurti and Wong 1979). Perhaps resulting from the strong correspondence between spatially locked features and the monsoon gyre, HOWI does not

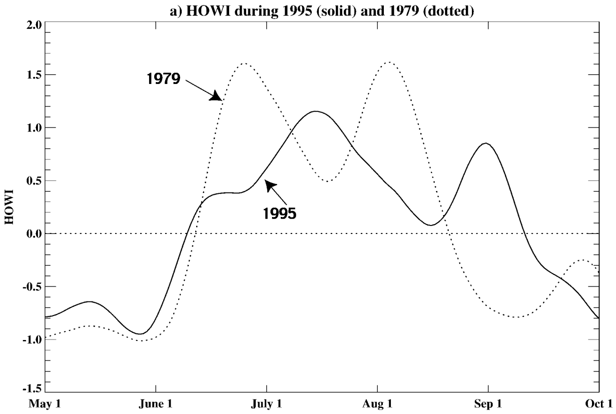

FIG. 7. Evolution of HOWI during 1995 (solid) and 1979 (dotted) when particularly strong ''bogus'' monsoon onsets occurred.

appear to confuse spatial and temporal fluctuations in the monsoon transitions.

c. *Resilience to bogus monsoon onsets and active-break transitions*

The monsoon is known to exhibit a false or bogus monsoon onset in some years associated with propagating tropical intraseasonal disturbances (e.g., Flatau et al. 2001). The bogus onset is characterized by enhanced convection and westerly surface winds similar to those that occur during monsoon onset but lasting a week or less. Often, bogus onsets are followed immediately by extended periods of weak winds and clear skies that result in heat waves and droughts in India. As bogus onsets can predate the actual onset by up to several weeks, it is particularly important for any onset determination to be insensitive to their occurrence.

Figure 7 shows the evolution of the HOWI index through two seasons in which exceptionally strong bogus onsets occurr as revealed by Flatau et al. (2001). Though variations in HOWI during both years are associated with the bogus onset in mid May, the HOWI criterion does not signal an onset until the first week of June when the monsoon onset actually occurs. Similarly, in 1979, the bogus onset in mid May, though evident in the HOWI time series, is insufficient to trigger the onset criterion. Rather, the onset as diagnosed by the HOWI occurs in early June. Thus, the HOWI index proves to be robust to two of the largest observed bogus onsets to occur in recent decades and signals correctly the early June onset of the monsoon.

Active–break transitions in the monsoon also induce variability in the HOWI (Fig. 7). As it is known that intraseasonal variability in the monsoon region is substantial (e.g., Rao 1976), an important characteristic of the HOWI is that it be resilient to false triggering from the active–break cycle of the monsoon itself. From Fig. 7, it can be seen that during both 1979 and 1995, transitions in HOWI from positive to negative represent the emergence and termination of the monsoon rather than intraseasonal active–break episodes and at no times within any of the monsoon seasons from 1948 to 2000 does the HOWI index change sign. Moreover, during most years from 1948 to 2000 the transition of the index across zero is monotonic and gradual and the index thus contains little ambiguity regarding the actual onset or withdrawal dates.

d. *Interannual variability in HOWI and connections to the monsoon season and ENSO*

Among the principle motivations for developing an improved index of monsoon onset is the role such an index may play in clarifying the relationships between the monsoon transitions, the strength of the monsoon season, and ENSO. Onsets and withdrawals identified by HOWI reveal basic associations that have previously been postulated (e.g., Joseph et al. 1994) but have not been shown to be strong in data. Table 3 shows the correlations between the onset as identified by HOWI and JJAS Indian rainfall, and JJAS Niño-3 SST. Table 4 shows the slope of the linear regressions between onset date and both JJAS Indian rainfall and JJAS Niño-3 SST. The associations show a strongly negative correlation between onset date and total JJAS rainfall indicating that a delayed (early) onset is associated with a

TABLE 3. Correlation of the hydrologic onset and withdrawal index (HOWI) with all India rainfall and JJAS Niño-3 SST. Also shown (left column) are the mean onset dates and standard deviations of onset dates from year to year. Results based on alternate selections of scale for the HOWI (2×10^6 km^2 and 7.5×10^6 km^2) are also shown in parentheses and correlations exceeding significance at the 99% confidence level are in bold.

Index (mean: std dev)	All India rainfall	Niño-3 SST
HOWI onset		
4 Jun: std dev = 7.4 days	**−0.33**	**0.37**
(2×10^6 km^2: 4 Jun: std dev = 7.4 days)	**(−0.31)**	**(0.37)**
(7×10^6 km^2: 5 Jun: std dev = 7.4 days)	**(−0.33)**	**(0.27)**
HOWI Withdrawal		
7 Sep: std dev = 11.0 days	**(0.58)**	−0.13
(2×10^6 km^2: 7 Sep: std dev = 11.0 days)	**(0.55)**	(−0.08)
(7×10^6 km^2: 2 Sep: std dev = 10.6 days)	**(0.59)**	(−0.18)

TABLE 4. Slope of the linear regressions that relate HOWI onset and withdrawal dates to all India rainfall and JJAS Niño-3 SST. Correlations between HOWI withdrawal and Niño-3 SST are weak and the regressions are thus less meaningful.

Index (mean: std dev)	All India rainfall	Niño-3 SST
HOWI onset	−27 days (100 mm)$^{-1}$	25 days °C^{-1}
(2×10^6 km^2)	[−29 days (100 mm)$^{-1}$]	(25 days °C^{-1})
(7×10^6 km^2)	[−27 days (100 mm)$^{-1}$]	(33 days °C^{-1})
HOWI withdrawal	23 days (100 mm)$^{-1}$	−106 days °C^{-1}
(2×10^6 km^2)	[25 days (100 mm)$^{-1}$]	(−173 days °C^{-1})
(7×10^6 km^2)	[22 days (100 mm)$^{-1}$]	(−75 days °C^{-1})

weaker (stronger) monsoon season. The slope of the linear regression is −27 days (100 mm)$^{-1}$. Monsoon withdrawal experiences a positive correlation with overall season rainfall (0.58) indicating that a delayed (early) withdrawal is associated with a stronger (weaker) monsoon season. The slope of the linear regression is 23 days (100 mm)$^{-1}$. HOWI-based onset date experiences a positive correlation with Niño-3 SST at 0.37 and a linearly regressed slope of 25 days °C^{-1}. HOWI withdrawal date experiences a weak negative correlation of −0.18 with Niño-3 SST and its linearly regressed slope of −106 days °C^{-1} is therefore of less significance. In general, however, warmer (cooler) SST in the east Pacific Ocean is associated with a delayed (early) monsoon onset and a shortened (extended) monsoon season.

Also shown in Tables 3 and 4 are the correlations and regressions achieved when alternative scales are used to construct the HOWI. The scales range from approximately 2×10^6 km^2 to 7×10^6 km^2, approximately half and twice the size of the region used to construct HOWI, respectively, and approximately 20–70 times the size of Kerala. Both the correlations of HOWI with other climate features and the values of their regression coefficients remain approximately constant for the alternative scales of identification. The correlations and regressions found with onset based on HOWI are robust to the scale of the averaging region chosen. Moreover, the correlations found between HOWI-derived onset date, total JJAS rainfall, and Niño-3 SST remain approximately twice as strong as those found in existing onset indices (Table 1). Thus, the speculation that approximately 50% of the variability in existing onset indices is unrelated to climate-scale variability suggested in Table 2 is also supported by the differences in correlations between existing and HOWI onset criterion and climate features such as ENSO and the monsoon season.

To illustrate further the correlations in Table 3, Fig. 8 shows the evolution of HOWI in two recent seasons in which ENSO events were present. In 1972, a warm event of 1°–2°C existed in the Pacific Ocean and the monsoon season, as diagnosed by HOWI, was shorter than average by about four weeks. The HOWI onset is identified on 16 June, 12 days after its climatological mean date of 4 June, and withdrawal is identified on 23 August, 14 days prior to its climatological mean date of 7 September. Conversely, the 1975 monsoon accompanied a cold event in the Pacific Ocean of 0.5°–1°C. Its onset is near normal (6 June) but its withdrawal is delayed by about a week (14 September). In both years, the length of the monsoon season is found to be inversely proportional to Niño-3 SST. However, recognizing that the correlation between the onset and SST is only 0.37, it is also important to note that there exist many causes of early and late monsoon onsets and several years in which the mean HOWI–ENSO relationships are not realized. Here the existence of the relationship during some years is merely illustrated.

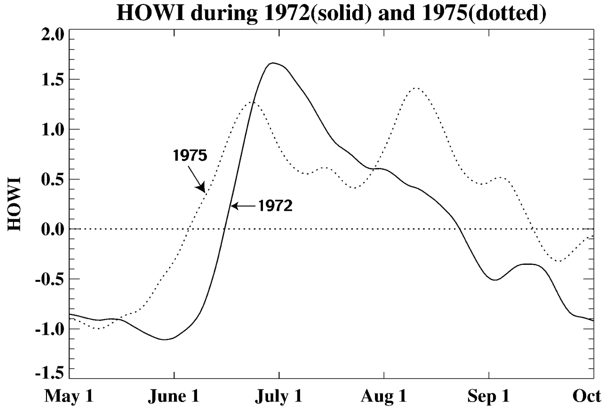

Fig. 8. Onset index during 1972 (solid) and 1975 (dotted) in which strong warm and cold events were present and accompanied by early and delayed onsets, respectively.

7. Conclusions

A retrospective diagnostic index of monsoon onset and withdrawal based on key features of the monsoon hydrologic cycle has been developed that provides new insight into the seasonal transitions of the Indian monsoon and their relationships to both total monsoon rainfall and ENSO. The index is intended to act as an indicator of interannual variability in the large-scale Indian monsoon system, rather than as a localized onset and withdrawal criterion, and is developed in hopes of further understanding the monsoon's relationship to ENSO and itself. The findings are consistent with the possibility that the method of the IMD and objective methods based on rainfall in a single Indian district are influenced, in part, by synoptic variability, the complex and variable spatial characteristics of monsoon onset, and subjective assessments of the monsoon circulation that are not indicative of the larger climate-scale transition.

An objective criterion is developed that spans very large spatial scales and is thus less sensitive to synoptic variability while being indicative of the rapid variations that occur during the monsoon transitions. The index is based on fields that are more accurately modeled and measured than rainfall. While the newly developed HOWI index shares about half of its variability with existing onset identifications, markedly increased and statistically significant relationships emerge between the monsoon transitions, JJAS rainfall, and ENSO when the new index is considered. The important associations revealed include a correlation between total JJAS rainfall and monsoon onset and withdrawal of −0.33 and −0.58, respectively. Also, correlations of Niño-3 SST with onset and withdrawal dates of 0.37 and −0.13 are found, respectively. In contrast to relationships derived from previous definitions of monsoon onset, many of the derived correlations exceed significance at the 99% confidence level. Both the relationships between HOWI and existing onset criteria, and the increased correlations that result between the HOWI-based onset dates, JJAS rainfall, and ENSO, are consistent with the interpretation that the associations have been masked somewhat in existing criterion by synoptic variability and spatial intricacies in the monsoon transitions. The performance of the newly derived HOWI index is found to be resilient to bogus onsets and active–break monsoon transitions. Future work includes the development of an operational version of the HOWI and further investigations of the potentially significant linkages that exist between the onset and withdrawal of the Indian monsoon and other components of the climate system.

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APPENDIX

Monsoon Onset and Withdrawal Dates

Monsoon onset and withdrawal dates determined by HOWI spanning the years 1948–2000 are listed.

Onsets			Withdrawals		
5 Jun 1948	15 Jun 1966	31 May 1984	8 Sep 1948	7 Sep 1966	2 Sep 1984
1 Jun 1949	12 Jun 1967	27 May 1985	28 Aug 1949	3 Sep 1967	4 Sep 1985
10 Jun 1950	11 Jun 1968	9 Jun 1986	21 Aug 1950	25 Aug 1968	21 Aug 1986
3 Jun 1951	12 Jun 1969	2 Jun 1987	27 Aug 1951	19 Aug 1969	9 Aug 1987
6 Jun 1952	30 May 1970	7 Jun 1988	29 Aug 1952	15 Sep 1970	26 Aug 1988
12 Jun 1953	27 May 1971	3 Jun 1989	31 Aug 1953	3 Sep 1971	1 Sep 1989
2 Jun 1954	16 Jun 1972	19 May 1990	25 Sep 1954	21 Aug 1972	11 Sep 1990
6 Jun 1955	5 Jun 1973	5 Jun 1991	11 Sep 1955	6 Sep 1973	5 Sep 1991
24 May 1956	18 Jun 1974	12 Jun 1992	30 Aug 1956	28 Aug 1974	8 Sep 1992
3 Jun 1957	7 Jun 1975	5 Jun 1993	10 Sep 1957	12 Sep 1975	10 Sep 1993
13 Jun 1958	30 May 1976	3 Jun 1994	18 Sep 1958	10 Sep 1976	13 Sep 1994
23 May 1959	8 Jun 1977	11 Jun 1995	16 Sep 1959	14 Sep 1977	12 Aug 1995
20 May 1960	4 Jun 1978	5 Jun 1996	4 Sep 1960	6 Sep 1978	22 Aug 1996
25 May 1961	13 Jun 1979	20 Jun 1997	27 Sep 1961	21 Aug 1979	2 Sep 1997
24 May 1962	1 Jun 1980	9 Jun 1998	24 Aug 1962	2 Sep 1980	22 Aug 1998
1 Jun 1963	9 Jun 1981	12 Jun 1999	12 Sep 1963	31 Aug 1981	13 Aug 1999
12 Jun 1964	6 Jun 1982	29 May 2000	3 Sep 1964	2 Sep 1982	3 Sep 2000
12 Jun 1965	14 Jun 1983	—	14 Aug 1965	15 Sep 1983	—

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