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A METHOD FOR DEFINING MONSOON ONSET AND DEMISE IN THE SOUTHWESTERN USA

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ABSTRACT

The southwestern USA is subject annually to an inflow of atmospheric moisture in association with the North American monsoon, which is a summertime shift in the atmospheric circulation stretching from the Caribbean Sea, to Mexico, and into the southwestern USA. There are currently no regional criteria used to define the temporal aspect of the annual monsoon season in the southwestern USA, and only a single local definition. A regionalized definition of the annual timing of the monsoon season would seem to be a greater representation of the synoptic-scale effects of the monsoon rather than individual definitions at point locations across the region. The research presented here outlines a method for defining the annual onset and demise of the regional monsoon season of the southwestern USA, and assesses the results through comparisons with a method currently used at one location within the region and with atmospheric composites from historic data.

Using hourly dew-point temperature data at five surface stations and daily precipitation data for 193 stations across the southwestern USA for June through to October for a 52 year period, daily humidity and precipitation threshold values indicative of monsoon moisture are established. The first and last occurrences of both humidity and precipitation sustained for a synoptic period of 3 days mark the annual onset and demise of the monsoon season, whereas all days in between that meet the humidity and precipitation thresholds are categorized as 'monsoon days'. Results show good agreement with sample historic data for the sole local definition within the region, and atmospheric composites indicate a likelihood of accurate representation of monsoon onset and demise across the region. The significance of accurate onset and demise dates is apparent in the intimate relationship between seasonal precipitation across the region and the length of the monsoon season. Based upon the procedure, a historic monsoon season database was constructed for the southwestern USA for use in climatological, meteorological, and case-study analyses. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: North American monsoon; humidity; precipitation; regional definition

1. INTRODUCTION

1.1. Background

The southwestern USA is subject annually to an inflow of atmospheric moisture in association with the North American monsoon (also referred to as the Southwest, Mexican, or Arizona monsoon), which is a summertime shift in the atmospheric circulation stretching from the Caribbean Sea, to Mexico, and into the southwestern USA. Across the southwestern USA, the seasonal shift from winds with generally a westerly component in winter and spring to winds with more of a southerly component typically establishes itself in early July and persists through to mid-September. Convective instability, associated with surface heating of the moist air, combined with orographic uplift, produces frequent convective precipitation events that are often associated with intense rainfall, lightning, hail, and damaging winds (e.g. McCollum *et al.*, 1995). As much as 50–70% of the annual rainfall across the southwestern USA and northwestern Mexico results from

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thunderstorms generated during the summer monsoon season (Carleton *et al.*, 1990; Douglas *et al.*, 1993; Higgins *et al.*, 1997; Mitchell *et al.*, 2002; Sheppard *et al.*, 2002).

The seasonal wind shift that is the monsoon across the southwestern USA is largely dependent upon the relative location of the typical northward-migrating subtropical ridge during the summer months (Carleton *et al.*, 1990; Watson *et al.*, 1994; Comrie and Glenn, 1998; Mullen *et al.*, 1998; Higgins *et al.*, 1998). The subtropical ridge, a mid-latitude ridge over the intermountain western USA, and a mid-latitude trough along the west coast of the USA are the primary upper-atmospheric synoptic-scale circulation features associated with the monsoon season of the southwestern USA (Figure 1(a)). Several studies have shown that a northward displacement of the subtropical ridge coincides with a wetter monsoon season across the region. When the ridge remains at a more southerly position, northward advection of tropical moisture is inhibited (Carleton, 1986; Carleton *et al.*, 1990; Adams and Comrie, 1997; Comrie and Glenn, 1998; Ellis and Hawkins, 2001; Hawkins *et al.*, 2002).

At the surface, the primary synoptic-scale features associated with the monsoon are a weak high-pressure centre in the Four Corners region of the USA (Arizona, Colorado, New Mexico, Utah), a thermal low-pressure area along the Colorado River valley, and to some extent the Bermuda high-pressure centre off of the southeastern coastline of the USA (Figure 1(b)). The three surface features act to draw lower and middle atmospheric moisture from a southerly direction to produce a clear pattern of increased lower-atmospheric moisture stretching from the western coastline of Mexico northward into the southwestern USA (Figure 1(c)). The source of moisture across the southwestern USA during the monsoon season has been debated for several

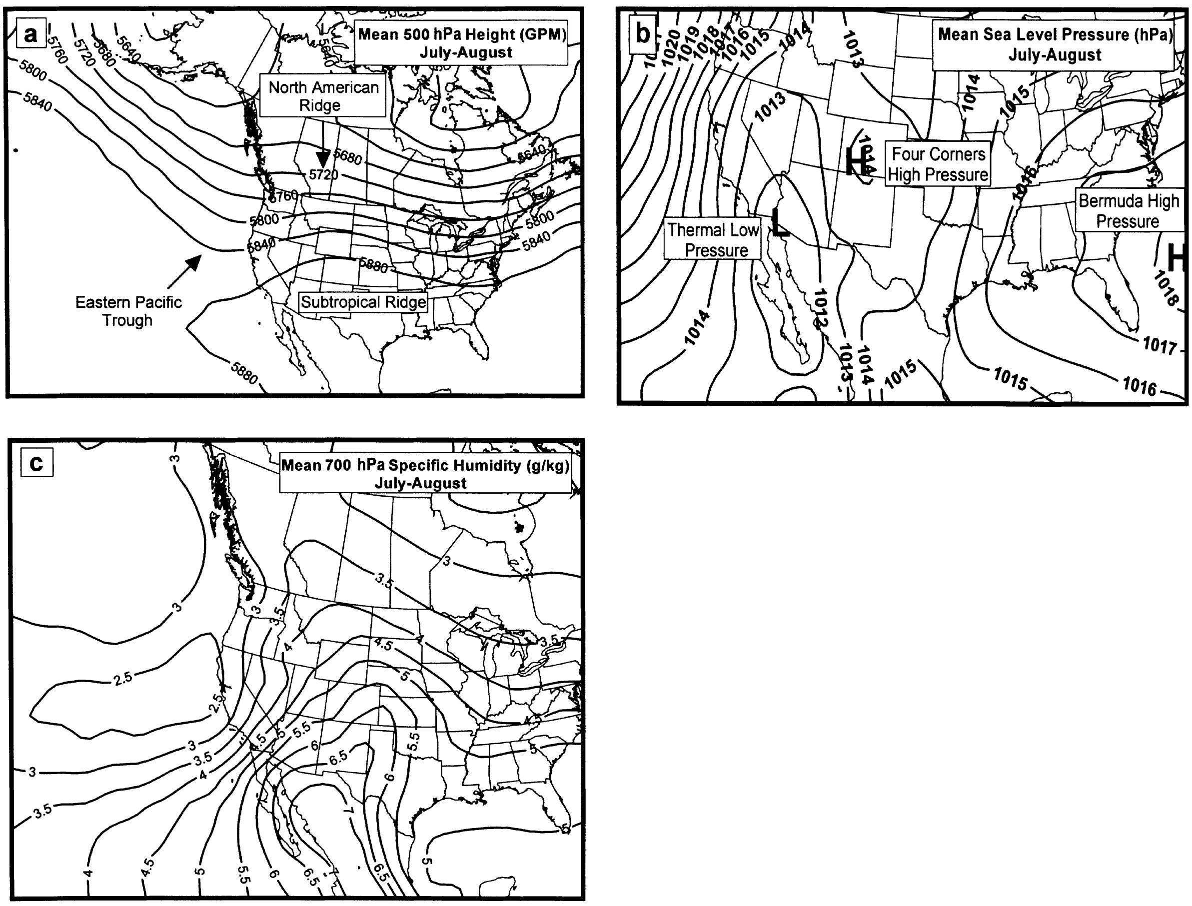

Figure 1. Features of the mean 500 hPa geopotential height pattern (a), mean sea-level pressure pattern (b), and mean 700 hPa specific humidity pattern (c) during July and August

decades (e.g. Rasmusson, 1967; Brenner, 1974; Hales, 1974; Carleton, 1986; Adams and Comrie, 1997). The general conclusion is that there exists a dual moisture source, with the Gulf of California being the major source, especially at low levels (Adams and Comrie, 1997). It is believed that southerly and southwesterly winds, including frequent low-level jet streams, advect moisture northward from the Gulf of California that is orographically lifted by the Sierra Madre Occidental, where it mixes with high-level moisture from the Gulf of Mexico as a secondary source. Intraseasonal variability occurs with 'bursts' and 'breaks' in moisture advection from the Gulf of California (Carleton, 1986; Adams and Comrie, 1997; Stensrud *et al.* 1997; Anderson *et al*., 2000; Fuller and Stensrud, 2000; Mitchell *et al*., 2002). As related to the synoptic features discussed above, Mullen *et al*. (1998) found the subtropical ridge to shift 5° of latitude northward in association with southeastern wind shifts in the middle and upper atmospheric levels and with 'bursts' in the northward advection of moisture.

In addition to the atmospheric circulation, the relationships between Pacific Ocean or Gulf of California sea-surface temperatures (SSTs) and the monsoon have been studied. Evidence was found to indicate that a cold anomaly in the northern Pacific Ocean coupled with a warm anomaly in the subtropical northern Pacific contributed to a wetter and earlier monsoon season (Higgins and Shi, 2000; Kingtse and Paegle, 2000; Mo and Paegle, 2000). Mitchell *et al*. (2002) found threshold SST values for the northern Gulf of California that were associated with what seemed to be the onset of the North American monsoon.

The spatial extent of the monsoon region within the southwestern USA can be well defined through examination of precipitation patterns created from a distribution of daily precipitation stations across the region. However, the criteria used to define the temporal aspect of the annual monsoon season, i.e. the specific dates of the onset and demise, are less well defined. At present, the criteria used for such a definition are not homogeneous throughout the southwest and there exists no authoritative body or set of guidelines for making this declaration for the region as a whole. Rather, at present, the only option for local National Weather Service Forecast Offices (NWSFOs) is to determine criteria specific to their point location (e.g. Dempsey *et al*., 1998). For instance, the Phoenix and Tucson, Arizona, NWSFOs (Figure 2(a)) define the start of the monsoon locally as the first day in the first 3 day sequence of mean daily dew-point temperatures of 55 °F (12.8 °C) and 54 °F (12.2 °C) or greater respectively. Thereafter, each individual day that reaches the dew-point threshold is considered to be a 'monsoon day', with the season at Phoenix extending through to an end date that is retroactively determined upon forecaster review of the late-season daily weather patterns (Phoenix NWSFO, 2003). The dew-point thresholds generally represent the surface moisture level that is reflective of an amount of precipitable water aloft necessary to yield a measurable amount of precipitation (Reitan, 1963). At Tucson, no end date for the annual monsoon season is declared, and at other NWSFOs in the monsoon region (Albuquerque, NM; El Paso, TX; Flagstaff, AZ) there exist no criteria for declaring the onset and demise of the monsoon. Within the southwestern USA the influence of the monsoon is realized by a change in the regional atmosphere to a condition of higher humidity and increased chance of precipitation. As such, it seems that a regional definition of the occurrence of the monsoon circulation is more sensible for use in annual declarations and in the development of a historical climatological database than the varied definitions used at individual stations, of which only two out of five NWSFOs in the region attempt.

Several indices of monsoon intensity have been devised for monsoon regions around the world: the all-Indian rainfall index (Shukla and Paolino, 1983; Shukla and Mooley, 1987), the Webster and Yang index (Webster and Yang, 1992), the monsoon Hadley circulation index (Goswami *et al*., 1999), the convection index (Wang and Fan, 1999), the dynamical normalized seasonality index (Li and Zeng, 2002), and the monsoon index that was derived specifically for the monsoon season of Arizona (Tenharkel, 1980). Most indices focus on representing the intensity of the well-known Indian monsoon. Applicable to any general monsoon circulation, including the North American monsoon, the dynamical normalized seasonality index of Li and Zeng (2002) focuses on monthly intensity as based on the strength of seasonal wind shifts, but does not aim at defining the annual beginning and ending of the monsoon season. The monsoon index of Tenharkel (1980) indicates the spatial coverage of rainfall during the monsoon portion of the year across Arizona by computing the fraction of reporting stations that experience measurable rainfall on a given day. A mean index value can then be calculated for a standard time period; however, the index does not derive a beginning or ending date of the monsoon season.

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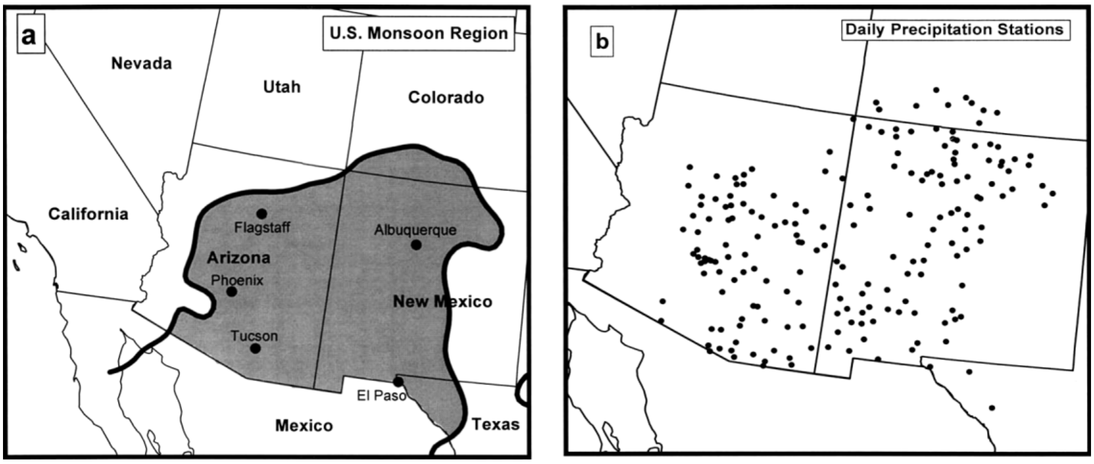

Figure 2. The monsoon region of the southwestern USA from the PCA of Hawkins *et al.* (2002) and the five meteorological stations (a), and the daily precipitation stations ($n = 193$) across the region (b)

As the large-scale North American monsoon circulation produces a rather homogeneous, regional field of moisture advection into the southwestern USA, it seems appropriate to define historically and declare annually the onset and demise of the monsoon on a regional basis. A regional determination might be a more robust method of identifying the onset and demise, rather than working beneath that scale by using individual definitions at point locations across the region, of which this is only done on a very minimal level at present. The region of the southwestern USA is positioned on the northern fringe of the North American monsoon, potentially making a representation of the annual monsoon season for the region a good indicator of the interannual variability of the strength of the monsoon circulation.

1.2. The monsoon region of the southwestern USA

In order to focus clearly on the variability and forecasting of the southwestern USA portion of the North American monsoon, it is first necessary to define the monsoon region systematically. Hawkins *et al.* (2002) defined the monsoon region of the southwestern USA by using principal components analysis (PCA) to determine the spatial pattern of monsoon season precipitation. Daily precipitation stations throughout the region of the southwestern USA containing 30 years of daily data through to 1997 were used in the PCA.

Component scores generated from the PCA for each station were used to create contour maps to delineate general areas of similar scores (positive (moister) versus negative (drier)). Clear patterns were associated with the first three components, which explained 29.5% of the variance. The first component was associated with an east–west gradient in scores and the second with a north–south gradient. The third component was associated with a tongue-like pattern in scores extending into the southwestern USA from Mexico, indicative of monsoon moisture advection. From the analysis of Hawkins *et al.* (2002), the 'monsoon' component of the PCA is used here to define the monsoon region of the southwestern USA (Figure 2(a)).

1.3. Temporally defining the monsoon season

The public demand for a declaration of the onset and demise of the monsoon largely extends from media outlets, and originates from public perception of the monsoon season as a significant, annual climatic event. Owing to the dramatic shift from dry, benign atmospheric conditions to a moister and convectively active atmosphere capable of providing over one-half of the region's annual precipitation, the public perception has credence. Anticipation of the onset of the monsoon season brings annual communication (television, newspaper, radio, Internet) of a meteorological understanding of the monsoon phenomenon and its effects, seasonal preparedness measures, pictures and video, and historical (Phoenix) comparisons.

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The method employed by the Phoenix NWSFO in determining the onset and demise of the annual monsoon season locally is the only full attempt at such a declaration. The NWSFO in Tucson only declares the onset, using a similar method to that used at Phoenix, whereas other NWSFOs make no such declarations regarding the monsoon season. The beginning of the monsoon season at Phoenix or at Tucson is defined as the first day of the first occurrence of three successive days during the summer months characterized by mean daily dew-point temperatures of 55 °F (12.8 °C) and 54 °F (12.2 °C) or greater respectively. Any subsequent day exhibiting a mean dew-point temperature equal to or greater than the threshold is classified as a 'monsoon day' up through to the ending date of the monsoon season. The end date at Phoenix is determined in retrospect by a forecaster upon the review of daily moisture conditions and atmospheric circulation patterns nearing the fall season. Using this method, the monsoon season at Phoenix traditionally begins on 7 July (Table I), but it has begun as early as 19 June and as late as 25 July. Similarly, the season typically begins at Tucson on 3 July (Table I), but it has begun as early 17 June and as late as 25 July. The season at Phoenix typically stretches across a 70 day period through to 14 September (earliest end date: 19 August; latest end date: 10 October), but it has been as short as 34 days and has persisted for as long as 104 days (Table I). Between the beginning and end of the monsoon, the mean number of monsoon days is 55, with a minimum of 27 days and a maximum of 99 days.

In developing a climatological definition of the annual monsoon season across the southwestern region of the USA, it is appealing to avoid definitions requiring detailed analysis of atmospheric dynamics simply due to the intensive study that would be required to construct a 50 year or greater historical dataset. From an operational monitoring perspective, difficulty exists in defining monsoon onset and demise based solely on wind shift, given the lack of a pronounced circulation shift in the rather stagnant atmosphere of the region. A more direct approach may simply be to monitor the product of the atmospheric shift — the moisture inflow itself and the associated occurrence of precipitation. Within a region characterized by an atmosphere that is typically very dry before and after the monsoon season (Comrie and Glenn, 1998), a simple definition based upon lower-atmospheric moisture and the occurrence of precipitation may work best. The use of dew-point temperature (such as at Phoenix and Tucson) and daily precipitation occurrence as the definitive 'monsoon day' criteria has practical applications. Near-surface dew-point temperature is easily recorded at several first-order meteorological stations across the southwestern USA, and daily precipitation is measured at many first-order and cooperative observing sites across the region ($n = 193$; Figure 2(b)). Researchers have shown that the diurnal amplitude of surface dew-point temperature is an important indicator of the likelihood of the development of convective thunderstorms in the region (Wallace *et al*., 1999). Furthermore, the use of dew-point temperature and/or precipitation is simple and more easily comprehended by the general public than would be the use of atmospheric dynamics.

In defining the onset and demise of the monsoon season, examination of lower atmospheric moisture and precipitation occurrence on a 3–5 day period seems sensible, in that a synoptic time frame associates well with a regional-scale event. The regional spatial scale should help to eliminate local effects at single stations (e.g. urban and elevation influences) and such potential problems as sub-regional-scale moisture from early-season tropical storm remnants.

Table I. Characteristics of the monsoon season as defined by the Phoenix, AZ, National Weather Service Forecast Office during the period 1948–97, including means, medians, standard deviations, minimum, and maximum values. Statistics are given for the beginning and ending dates, length, and number of monsoon days. Statistics for the beginning date as defined by the Tucson, AZ, office (TUC) are also given

	Mean	Median	SD (days)	Minimum	Maximum
Beginning date	7 July	7 July	7.8	19 June	25 July
Beginning date (TUC)	3 July	3 July	7.5	17 June	25 July
Ending date	14 September	14 September	12.0	19 August	10 October
Season length (days)	69.6	69.5	15.5	34	104
Monsoon days (days)	55.5	55.5	15.5	27	99

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The attempt to define the annual onset and demise of the monsoon climatologically across the southwestern USA, therefore, involves a blend of regionalized daily dew-point temperatures and precipitation occurrence on a synoptic time scale as the indicator. The ultimate objective is to construct a regional monsoon-season database for the northern fringe of the North American monsoon (the southwestern USA), such that interannual variability and the atmospheric drivers can be more confidently studied. A final goal is for the methodology employed here to provide a regional definition of the monsoon season for a more formal declaration annually.

2. DATA AND METHODOLOGY

Hourly dew-point temperature data for first-order weather stations within the monsoon region (Figure 2(a)) were extracted from the Daily Surface Database (TD-3210) of the National Climatic Data Center (NCDC). Requiring a completeness of record for the period 1950 through to 2001 limited the number of stations to five: Tucson (elevation: 776 m), Phoenix (336 m), and Flagstaff (2124 m) in Arizona (eliminating Douglas and Winslow); Albuquerque, NM (1609 m; eliminating Gallup and Las Vegas); and El Paso, TX (1194 m; Figure 2(a)). Mean daily dew-point temperatures at each station were created from hourly and, infrequently, three-hourly dew-point temperatures and then simply translated to a regional daily average using all five stations weighted equally.

The determination of a dew-point temperature threshold to characterize a particular day as regionally moist is potentially difficult. Here, quite simply, the record of mean daily regional dew-point temperature within the seasonal period for which the monsoon is typically operational is stratified in half — those that were relatively moist and those that were relatively dry. For the 52 year study period, the median of the mean daily regional dew-point temperatures for the period 15 June through to 15 October (covering the extreme onset and demise dates as defined at Phoenix) is 50.23 °F (10.13 °C) and represents the midpoint in the distribution of historic data. This suggests that any day characterized by a regional mean dew-point temperature of 50.23 °F (10.13 °C) or greater is a relatively moist day. Median values of mean daily dew-point temperatures for the same time periods for Tucson (53.88 °F (12.16 °C)) and Phoenix (54.50 °F (12.50 °C)), Arizona, individually compare nicely with dew-point threshold values that are currently in use at each location (Tucson 54 °F (12.2 °C); Phoenix 55 °F (12.8 °C)). *Median* values are used here to stratify the data simply because *mean* values of daily dew points in the dry southwestern USA tend to be significantly skewed toward lower values. The frequency of an occasional extremely low daily dew-point temperature (outlier) is much greater than that of an extremely high daily dew point within the arid environment. When median values are rounded to whole numbers, a set of threshold dew-point temperatures for the five individual stations and the region is defined (Table II).

In employing regional rainfall in the determination of the annual onset and demise of the monsoon, a method similar to that employed in the development of the Tenharkel (1980) monsoon index for Arizona is used. Using 193 stations from across the monsoon region (Figure 2(b)), the percentage of reporting stations experiencing measurable rainfall on a given day is calculated for the same period used in analysing mean

Table II. Dew-point temperature thresholds for each of the five stations within the monsoon region and for the monsoon region as a whole

Station/area	Dew-point temperature (°F [°C])	
	Actual	Defined
Flagstaff	40.75 [4.86]	41 [5.00]
Albuquerque	46.92 [8.29]	47 [8.33]
El Paso	53.04 [11.69]	53 [11.67]
Tucson	53.88 [12.16]	54 [12.22]
Phoenix	54.50 [12.50]	55 [12.78]
Region	50.23 [10.13]	50 [10.00]

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regional daily dew-point temperatures, 15 June through to 15 October. As with mean regional dew-point temperature, a threshold value for precipitation occurrence across the region is established using the median daily value for the period analysed. The median of the fraction of stations reporting measurable precipitation on a given day during the typical timing of the monsoon season is 19.5%, and is rounded here to 20%. This is to say that if 20% or greater of the 193 precipitation stations across the region report rainfall, then the regional coverage of precipitation was greater than what is typical, suggesting that the day is regionally moist.

Similar to the current definition of the beginning of the monsoon season in Phoenix, the beginning of the season as defined here is the first day of the first occurrence of a 3 day period for which the regional mean daily dew-point temperature is 50 °F (10 °C) or greater and the regional coverage of daily precipitation is 20% or greater. This would suggest the occurrence of the first moist synoptic event of the season across the region. Likewise, the end of the season is defined as the last day of the last occurrence of such an event, — i.e. of the last three successive days of a mean regional daily dew-point temperature of 50 °F (10 °C) or greater and a regional coverage of daily precipitation of 20% or greater. This eliminates the current need for intensive study of the atmospheric dynamics to determine the end date, as is currently done at Phoenix. There still exists the danger of incorporating the effects of a renegade mid-latitude system and its associated moisture into the determination of the onset and demise. However, this risk should be lessened through the use of the regional humidity and precipitation criteria, as mid-latitude systems just prior to or after the season do not often produce homogeneous moisture fields in the southwestern USA for a full 3 day synoptic period. Rather, mid-latitude systems would most often be marked by upper-atmospheric shortwave systems propagating through the region, acting much like a surface frontal boundary moving through the region on a time scale of less than 3 days.

In an attempt to help validate the results, sample atmospheric composites from the record of monsoon-season beginning and ending dates are constructed from the reanalysis database of the National Centers for Environmental Prediction (Kalnay *et al.*, 1996) to judge better the effectiveness of the method. Primarily, composites of regional humidity at the 700 hPa pressure level are used, but also fields of geopotential height at the 500 hPa level, sea-level pressure, daily precipitation rate, and surface air temperature are constructed. In examining the beginning and ending dates for the period 1950 through 2001, composites of specific humidity at the 700 hPa height level were constructed for the 3 days preceding a beginning date along with the first 3 days of the monsoon season, for a total of six composites. Similar composites were constructed from the same sample of years but for the last 3 days of the monsoon season along with the first 3 days after the end of the season.

The greatest application of this work should stem from the historical determination of the beginning and end of the monsoon season. Simple accounting of humidity and precipitation between the first and last days should characterize the season well. However, labelling ‘monsoon days’ may have some value. Inclusive of the first and last days of the monsoon season, any day meeting the mean regional daily dew-point temperature threshold of 50 °F (10 °C) and the fraction of regional stations receiving a precipitation threshold of 20% is classified as a ‘monsoon day’.

Beyond the calculation of descriptive statistics for the regional monsoon season (beginning, end, length, number of ‘monsoon days’), several additional variables are constructed to form a more comprehensive regional monsoon season database. Calculated from the daily precipitation data used in the determination of the onset and demise of the annual monsoon is the annual average monsoon season precipitation across the region and the mean frequency of precipitation within the region for each year. Regional seasonal means of dew-point temperature and precipitation occurrence, and the same stratified by monsoon day and non-monsoon day, are also calculated.

In order to examine seasonal differences between wet and dry monsoon seasons across the southwestern USA, descriptive statistics for the monsoon season are produced for anomalous years as determined by the magnitude of mean regional precipitation. Years for which the mean regional precipitation was one standard deviation or greater from the mean, positive or negative, are considered wet or dry years, and the descriptive statistics are recalculated for these subsets of years.

Finally, any onset and demise dates that were one standard deviation or greater from the mean onset and demise dates were identified as outliers for additional study. The population of years characterized by

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anomalous onset and demise dates were gathered to produce atmospheric composites of 500 hPa geopotential height for the months of May through to July for early/late onsets, and for the months of August through to October for early/late demises. The goal is to identify differences in the synoptic atmosphere associated with the anomalous dates.

3. RESULTS AND DISCUSSION

3.1. Regional monsoon definition

Descriptive statistics best assess the results of the method used to define the monsoon season regionally, especially when compared with the representative data for the only local site with a full definition, i.e. Phoenix (also, comparison with onset definition at Tucson). In comparing the statistics, it should be noted that data from the method currently in use at Phoenix are derived from the period 1948 through to 1997, whereas data from the procedure outlined here cover the period 1950 through to 2001. The method outlined here results in a typical regional start date of the monsoon of 5 July (Table III; Figure 3(a)), comparable to the dates established at Phoenix and Tucson (Table I). The earliest start date of 5 June (Table III; Figure 3(a)) is 2 weeks earlier than that currently defined for Phoenix (19 June; Table I), the validity of which is discussed later. The next earliest date produced by the method outlined here, 17 June in 1958, is more comparable and matches that in Tucson (Table I). The latest monsoon start date of 25 July (Table III; Figure 3(a)) equals that in the local record at Phoenix and Tucson (Table I).

The typical monsoon season ending date produced by the process used here is 14 September (Table III; Figure 3(a)), equalling that for Phoenix (Table I). The earliest and latest end dates as defined here (18 August and 9 October respectively; Table III; Figure 3(a)) compare well with those already derived for Phoenix (19 August and 10 October respectively; Table I). With start and end dates that are slightly earlier and later respectively than as defined at Phoenix, the method employed here produces a mean monsoon season that is longer (73 days; Table III; Figure 3(b)). The shortest seasons compare well (33 days for the new method; 34 days for the Phoenix method), whereas the longest season under the method presented here (1972) is much longer (125 days versus 104 days) due to the very early starting date for that particular year (5 June 1972).

With the consideration of both moisture and precipitation across the entire region, rather than at a single station, the method presented here produces a slightly smaller mean number of 'monsoon days' (49; Table III; Figure 3(a)) than the method currently in use in Phoenix (55; Table I). This is to say that the local Phoenix dew-point threshold is traditionally met more often than the regional criteria needed for classification as a

Table III. Descriptive statistics for the regional monsoon season, 1950–2001, including means, medians, standard deviations, minimum, and maximum values. Statistics are given for the beginning and ending dates, length, number of monsoon days, and the mean dew-point temperatures and percentage of stations reporting precipitation for the season, monsoon days, and non-monsoon days

Variable	Mean	Median	SD	Minimum	Maximum
Beginning date	5 July	5 July	9.3	5 June	25 July
Ending date	14 September	14 September	13.7	18 August	9 October
Season length (days)	72.9	73.0	18.2	33	125
Monsoon days (days)	48.4	49.0	11.3	23	74
Seasonal T_d (°F [°C])	53.5 [11.9]	53.3 [11.8]	2.0 [1.1]	48.4 [9.1]	56.9 [13.8]
Monsoon day T_d (°F [°C])	56.2 [13.4]	56.3 [13.5]	1.1 [0.6]	53.9 [12.2]	59.1 [15.1]
Non-monsoon day T_d (°F [°C])	48.3 [9.1]	48.2 [9.0]	2.7 [1.5]	43.2 [6.2]	53.9 [12.2]
Stations reporting precipitation (%)					
Seasonal	30.9	30.4	4.6	21.4	40.7
Monsoon days	40.3	40.2	3.0	32.1	46.8
Non-monsoon days	11.6	11.3	3.4	2.8	21.3

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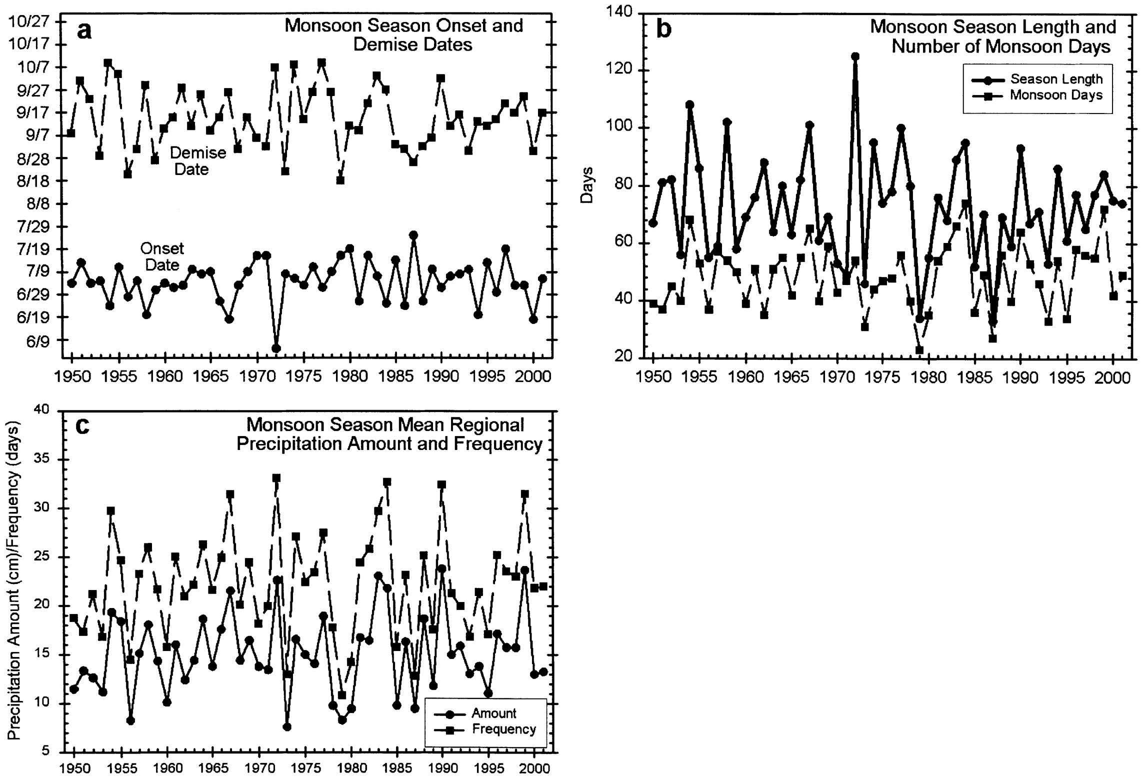

Figure 3. Monsoon onset and demise dates (a), season length and number of monsoon days (b), and mean regional precipitation amount and frequency (c) for the period 1950 through to 2001

'monsoon day'. The mean regional dew-point temperature on a monsoon day (56.2 °F (13.4 °C)) is, on average, approximately 8 °F (approximately 4 °C) higher than on non-monsoon days (48.3 °F (9.1 °C); Table III). On average, a monsoon day is characterized by approximately 40% of the region receiving rainfall, whereas on a non-monsoon day only about 11% of the stations record rain (Table III). A location within the monsoon region receives approximately 15 cm of rainfall on average during the monsoon season from approximately 22 days of measurable precipitation (Figure 3(c)). The amount of seasonal rainfall across the region is highly related to the length of the season, as Pearson correlation coefficients between mean regional precipitation and the onset ($r = -0.48$) and the demise ($r = +0.66$) dates across the 52 year period are both very significant ($p = 0.00$).

The most obvious outlier in the monsoon onset and demise dates derived by the procedure presented here is the very early onset date in June 1972. However, the early start date of 5 June 1972 seems reasonable when considering lower-atmospheric humidity patterns across the region and the anomalous atmosphere that is in place at that time. Regional humidity increased from 2 June through to 7 June, where the regional mean dew-point temperature peaked at 2.5 °F (1.4 °C) above the threshold value of 50 °F (10 °C; Figure 4(a)). The regional mean dew-point temperature was above the threshold for the 4 day period of 5–8 June. The same can be said of the pattern of daily precipitation occurrence, as the percentage of stations recording precipitation increased from near 10% on 2 June to nearly 58% on 7 June. Across the 4 day period of 5–8 June, the percentage of stations reporting daily rainfall ranged between 40 and 60%.

A concern with a very early start date is that it is a reflection of an unusually southerly mid-latitude system or of the remnants of a tropical system. Synoptic composites of anomalies of 700 hPa moisture, 500 hPa height, sea-level pressure, and daily precipitation rate for the 4 day period 5–8 June 1972 provide further evidence that the moisture seems to have been synoptic in nature and unassociated with a mid-latitude or a tropical low-pressure centre. For the 4 day period, intense ridging in the 500 hPa height pattern existed across

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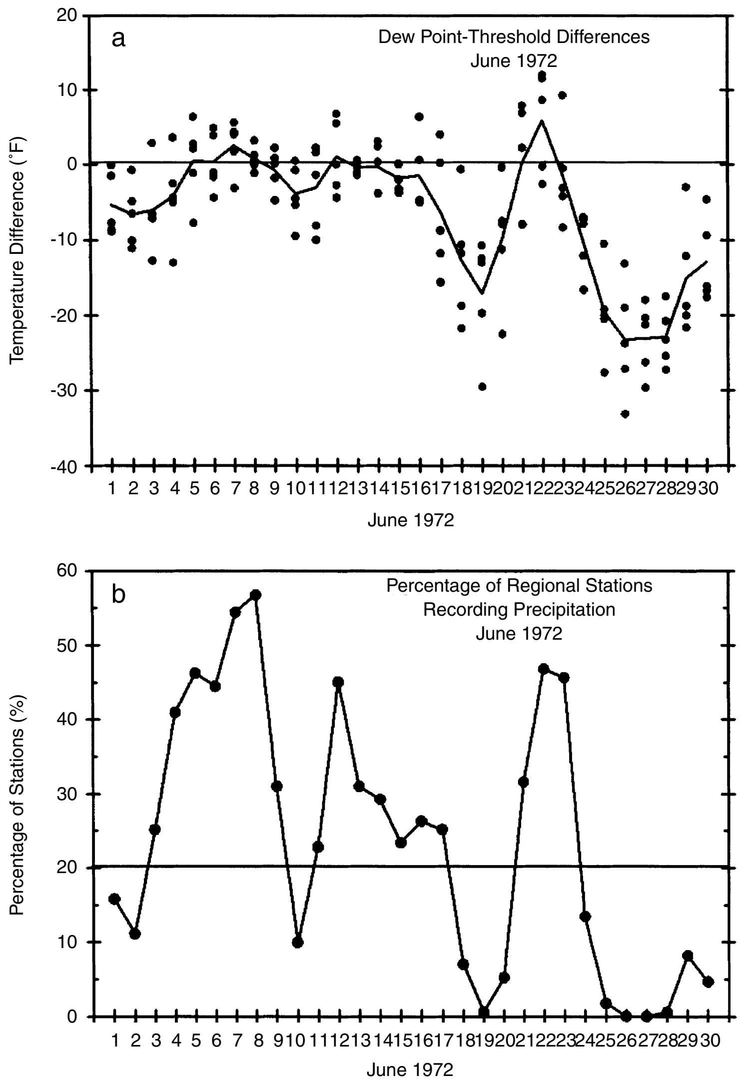

Figure 4. The difference in mean daily dew-point temperatures from threshold values for the region (solid line) and for the five stations (dots) (a), and the daily regional precipitation frequency (%) relative to the threshold (b) for June 1972

the central USA and Canada, coupled with a deepening of the typical trough along the west coast of North America (Figure 5(a)). The heightened ridge and deepened trough are consistent with the general pattern associated with a more active monsoon. The anomalous 500 hPa height pattern was associated with higher than typical sea-level pressure values through the central portion of the USA, especially in the panhandle area of Texas and northwestward toward the Four Corners region (Figure 5(b)). Intensification and/or eastward displacement of a typical weak anticyclone in the Four Corners region of the USA is likely to be associated with moist southerly flow to its west across the monsoon region. This is clearly evident in the pattern of mean 4 day 700 hPa specific humidity (Figure 5(c)), as large positive anomalies are evident from western Mexico, northward through the monsoon region, and wrapping clockwise around the greatest sea-level pressure anomaly into the central plains. The atmosphere at and east of the location of the greatest pressure anomaly was much drier than is typical (Figure 5(c)). Lastly, the mean daily precipitation rate for the 4 day period indicates an axis of rainfall that stretches from western Mexico northward through the monsoon region (Figure 5(d)), providing further evidence of an apparent monsoon-like situation. After the apparent start of

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the monsoon in early June 1972, there were a couple of periods (12 June and 21–23 June) of monsoon-like moisture across the region (Figure 4(a) and 4(b)). This could be an illustration of 'bursts' of moisture into the region from the south.

3.2. Atmospheric composites

The composite 700 hPa specific humidity pattern 3 days prior to the monsoon season start date shows a rather dry atmosphere across the monsoon region, with approximate values between 4 and 5.5 g/kg (Figure 6(a)). Virtually the same pattern holds at 2 days prior to the start of the monsoon season (Figure 6(b)); however, moisture levels increase by the day prior to the start of the monsoon season (Figure 6(c)). At 1 day prior to the monsoon season start date, specific humidity values range from about 4.5 to 6 g/kg, and the tongue of higher moisture levels south and southeast of the USA monsoon region expands northward. On the day that represents the beginning of the monsoon season, specific humidity values across the monsoon region expectedly increase to a general range from 5 to 6.5 g/kg (Figure 6(d)). Specific humidity across the monsoon region increases to between 6 and 7 g/kg by the second day of the monsoon season (Figure 6(e)), and values on the third day of the season increase to above 7 g/kg over the southeastern portion of the region (Figure 6(f)).

At the end of the monsoon season, the composites of daily 700 hPa specific humidity 2 days and 1 day prior to the end date of the monsoon season show moisture extending northward to produce values of

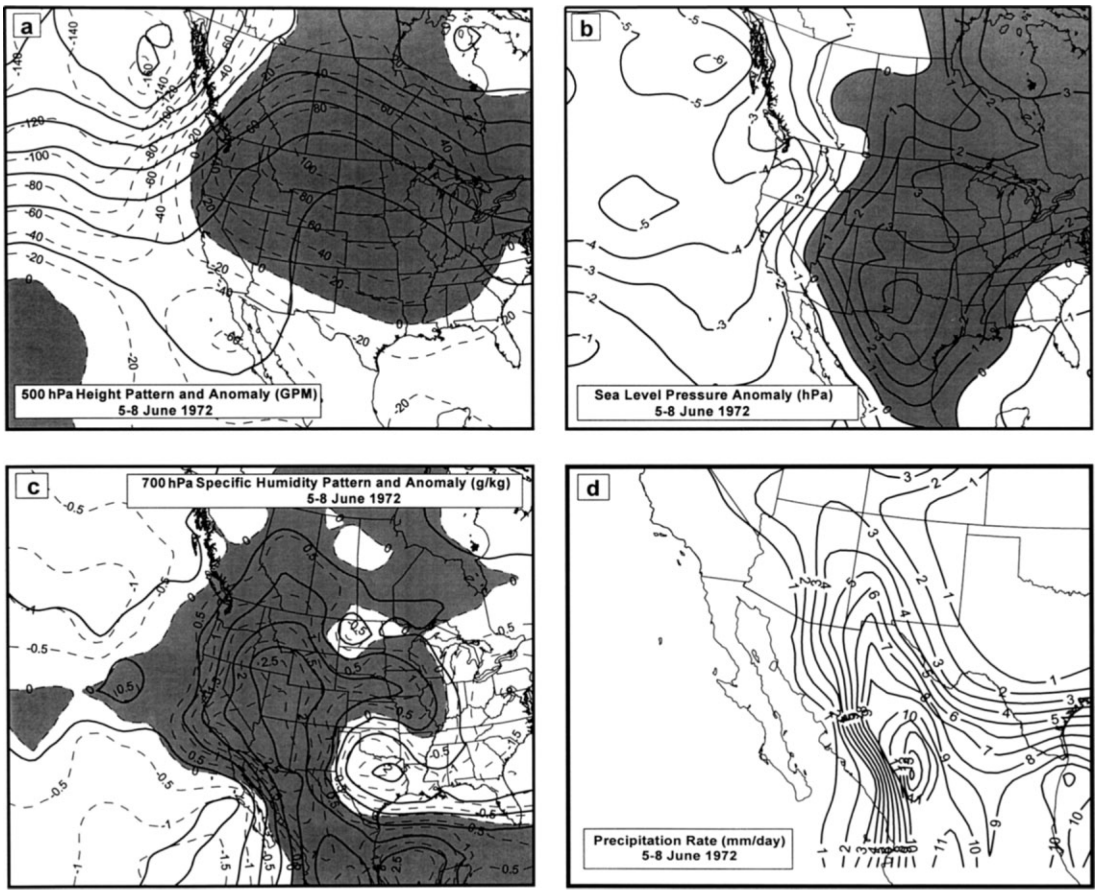

Figure 5. The mean 500 hPa height pattern and anomaly (a), sea-level pressure anomaly (b), 700 hPa specific humidity pattern and anomaly (c), and mean daily precipitation rate (d) for 5–8 June 1972. Height and humidity anomalies are dashed, and all positive anomalies are shaded

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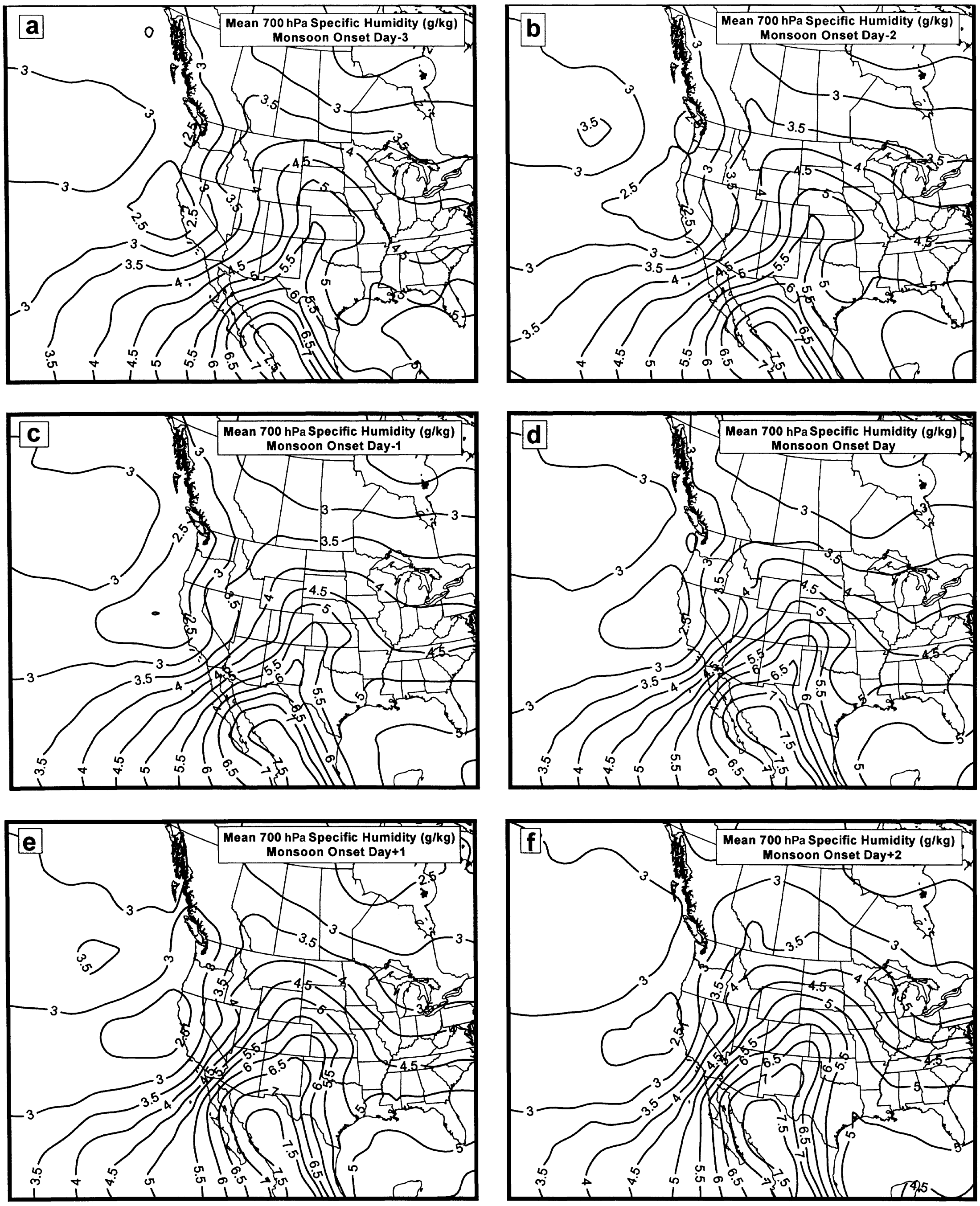

Figure 6. Composites of 700 hPa specific humidity at 3 days (a), 2 days (b), and 1 day (c) prior to the onset of the monsoon (d), and 1 day (e) and 2 days (f) after the onset of the monsoon

between 5.5 and 7 g/kg across the monsoon region (Figure 7(a) and (b)). In fact, on the second-to-last day of the monsoon season, humidity values actually increase a bit along the eastern portion of the region, as if humidity is begin drawn a bit further north in advance of a mid-latitude system. By the last day of the monsoon season, humidity values across the monsoon region, especially along the western edge, decrease to between 5 g/kg and less than 7 g/kg (Figure 7(c)). Specific humidity across the monsoon region decreases

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dramatically on and after the ending date for the monsoon season, from between 4.5 and 6 g/kg on the day after (Figure 7(d)), to between 4 and 5.5 g/kg 2 days afterward (Figure 7(e)), to between 4 and 5 g/kg 3 days afterward (Figure 7(f)).

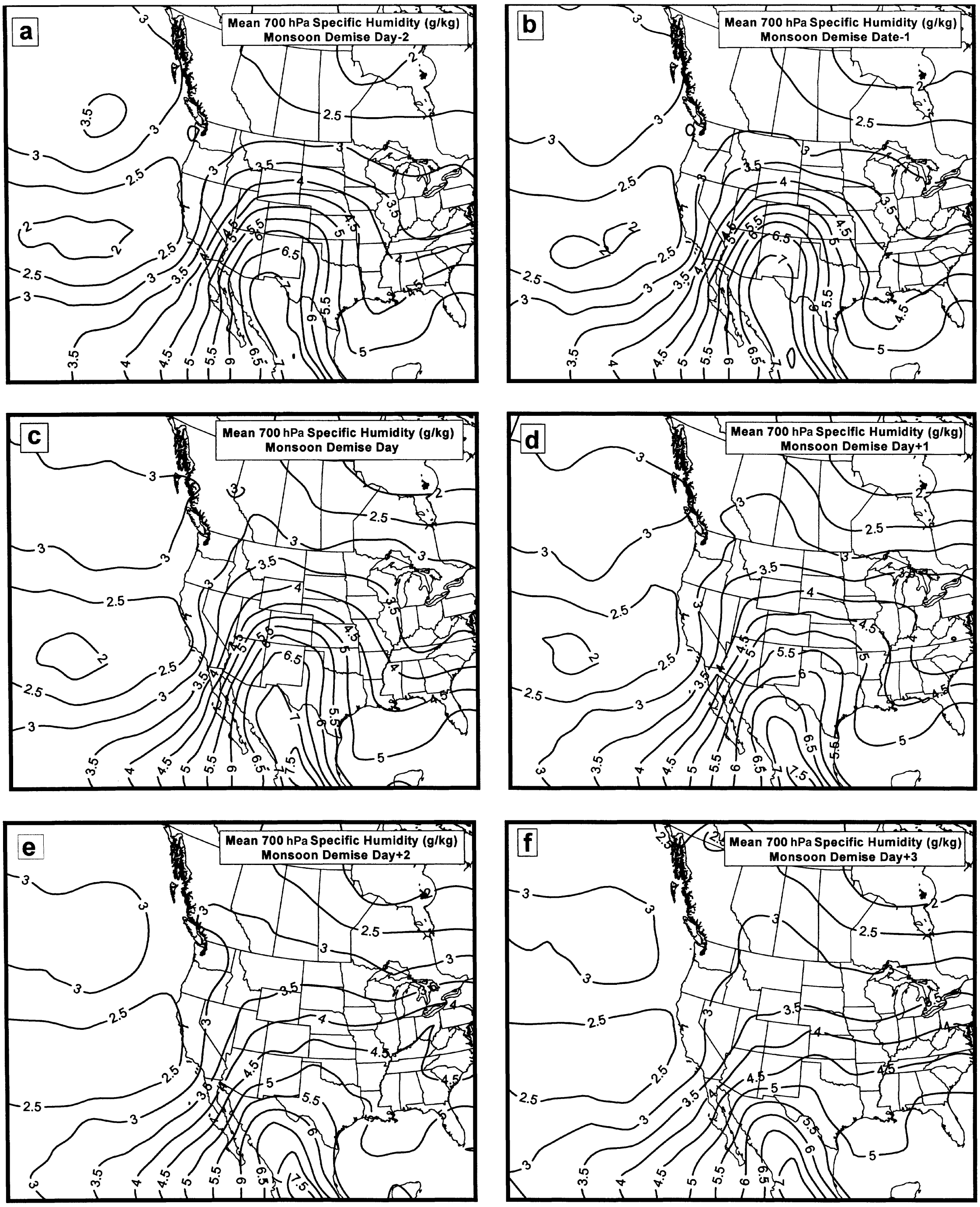

Figure 7. Composites of 700 hPa specific humidity 2 days (a) and 1 day (b) prior to the demise of the monsoon (c), and 1 day (d), 2 days (e), and 3 days (f) after the demise of the monsoon

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3.3. Seasonal anomalies

The identification of wet ($n = 7$) and dry years ($n = 8$) as anomalous regional precipitation seasons (±1 standard deviation from the mean) allowed for recalculation of seasonal statistics (e.g. Table III) to demonstrate the interrelationships of the characteristics of the monsoon season. As might be expected, wet seasons (Table IV) are marked by earlier start dates (10 days) and later end dates (18 days) than average (Table III). In contrast, dry seasons (Table V) are marked by later start dates (7 days) and earlier end dates (14 days) than average (Table III). On average, wet seasons are approximately 46 days longer than dry seasons (Tables IV and V) and produce roughly twice the number of monsoon days (66 versus 33). Only minor differences exist in the mean dew-point temperatures on monsoon and non-monsoon days during wet seasons and those during dry seasons (dry seasons slightly lower). The same is true for the percentage of regional stations reporting precipitation: little difference is evident between wet and dry seasons. This suggests an importance of season length in the interannual variability of the monsoon season, as days within the season are very similar between wet and dry years; quite simply, there are more monsoon days during wet seasons. This similarity of the individual days can be seen by considering the percentage of days within each type of season (wet/dry) that are monsoon days: 66% in the case of wet years and 63% in the case of dry years. With the days of each type of year being similar, and their relative frequency within the season being similar, the controlling variable is the length of the season.

The identification of outliers in the record of annual monsoon onset demise dates for the period 1950 through to 2001 produced 8 years of early onsets and 8 years of onsets much later than usual. Synoptic

Table IV. Same as Table III, but for 'wet' monsoon years

Variable	Mean	Median	SD	Minimum	Maximum
Beginning date	25 June	25 June	10.9	5 June	7 July
Ending date	1 October	2 October	5.7	24 September	9 October
Season length (days)	99.3	95.0	13.8	84	125
Monsoon days (days)	66.1	66.0	6.5	54	74
Seasonal T_d (°F [°C])	53.4 [11.9]	54.1 [12.3]	2.6 [1.4]	48.4 [9.1]	56.6 [13.7]
Monsoon day T_d (°F [°C])	56.0 [13.3]	56.1 [13.4]	1.2 [0.7]	54.0 [12.2]	57.7 [14.3]
Non-monsoon day T_d (°F [°C])	48.2 [9.0]	48.5 [9.2]	2.1 [1.2]	44.1 [6.7]	50.0 [10.0]
Stations reporting precipitation (%)					
Seasonal	32.2	33.4	4.0	26.5	37.5
Monsoon days	41.6	41.2	2.2	38.4	45.3
Non-monsoon days	11.9	11.9	1.8	9.1	13.8

Table V. Same as Table III, but for 'dry' monsoon years

Variable	Mean	Median	SD	Minimum	Maximum
Beginning date	12 July	12 July	8.6	28 June	25 July
Ending date	1 September	30 August	13.4	18 August	26 September
Season length (days)	53.0	53.5	16.1	33	80
Monsoon days (days)	33.5	35.5	6.0	23	40
Seasonal T_d (°F [°C])	52.8 [11.6]	52.8 [11.6]	1.7 [0.9]	50.5 [10.3]	55.4 [13.0]
Monsoon day T_d (°F [°C])	55.6 [13.1]	55.5 [13.1]	1.2 [0.7]	54.2 [12.3]	58.0 [14.4]
Non-monsoon day T_d (°F [°C])	47.2 [8.4]	47.7 [8.7]	2.6 [1.4]	43.2 [6.2]	51.1 [10.6]
Stations reporting precipitation (%)					
Seasonal	28.3	27.2	5.4	22.2	38.8
Monsoon days	37.7	36.5	4.8	32.1	46.8
Non-monsoon days	9.0	10.0	2.9	2.8	11.6

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composites of the differences in the mean monthly 500 hPa height patterns for the two sets of years were constructed for the months of May, June, and July (Figure 8). In May, the composites show that early (late) onset years were marked by height increases (decreases) over the southwestern USA and a strengthened (weakened) southerly portion of the typical Pacific ridge (Figure 8(a)). This is to say that early (late) onset years were marked by an early (late) northward (southward) shift in the 500 hPa height pattern from the central USA westward into the Pacific Ocean. North and east of this region the heights were lower (higher) in early (late) onset years.

During June, the emphasis shifts to the ridge–trough pattern of the eastern Pacific Ocean and heights over the eastern USA, whereby both are increased (decreased) during years of an early (late) onset (Figure 8(b)). Between the two areas, the typical North American ridge is marked by height decreases (increases) during early (late) onset years, weakening (strengthening) the ridge. By July, years during which the onset of the monsoon season was early (late) were again marked by higher (lower) heights in the vicinity of the eastern Pacific ridge–trough pattern, extending into the southwestern USA (Figure 8(c)). Across the eastern USA, heights were lower (higher) during early (late) onset years.

Taken together, the composites for the 3 months seem generally to indicate a deamplification of the ridge–trough pattern from the eastern Pacific Ocean eastward into western North America during early onset years. During the period, the eastern Pacific–western North American trough is marked by higher heights, and the western North American ridge is marked by lower heights in May (Canada), June, and July (Canada and USA). In the meantime, the Pacific ridge is marked by higher heights, as is the eastern USA in June.

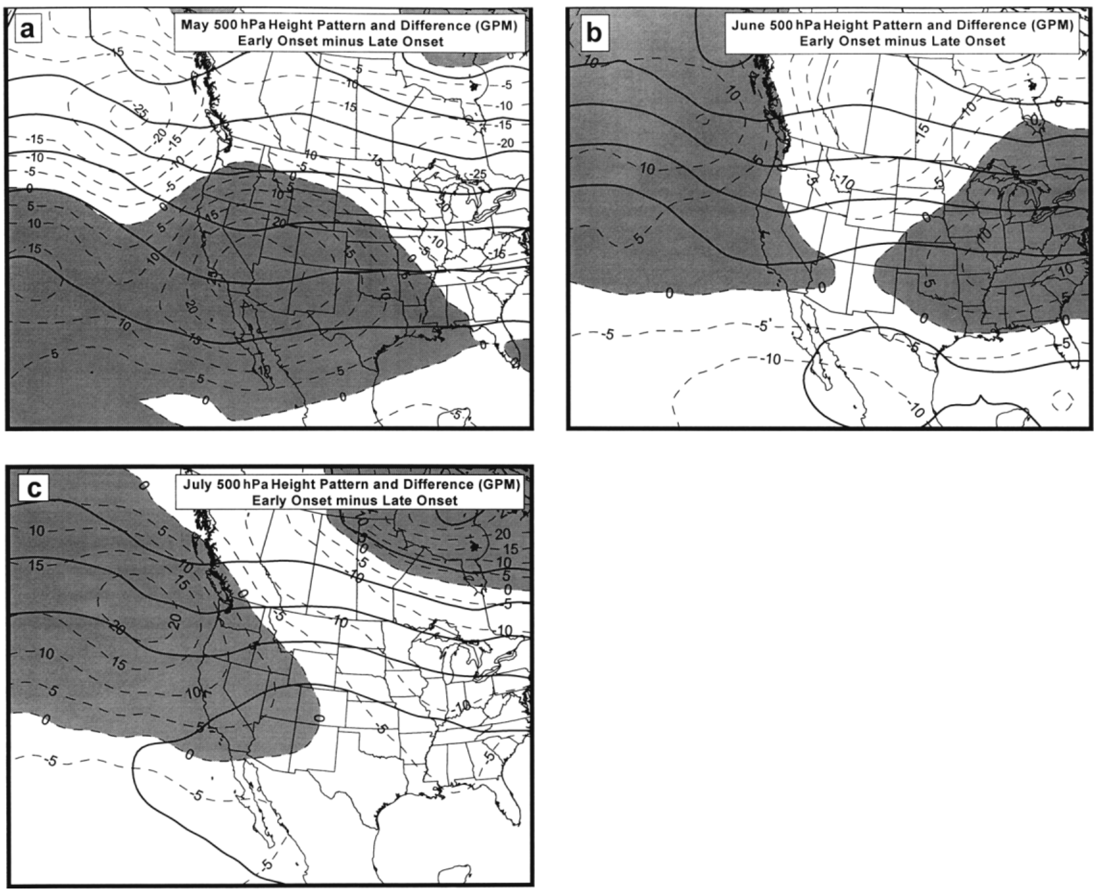

Figure 8. Mean 500 hPa height pattern (solid) and differences (dashed) between years of early and late monsoon onset for May (a), June (b), and July (c). Differences are taken as early onset minus late onset, and positive differences are shaded

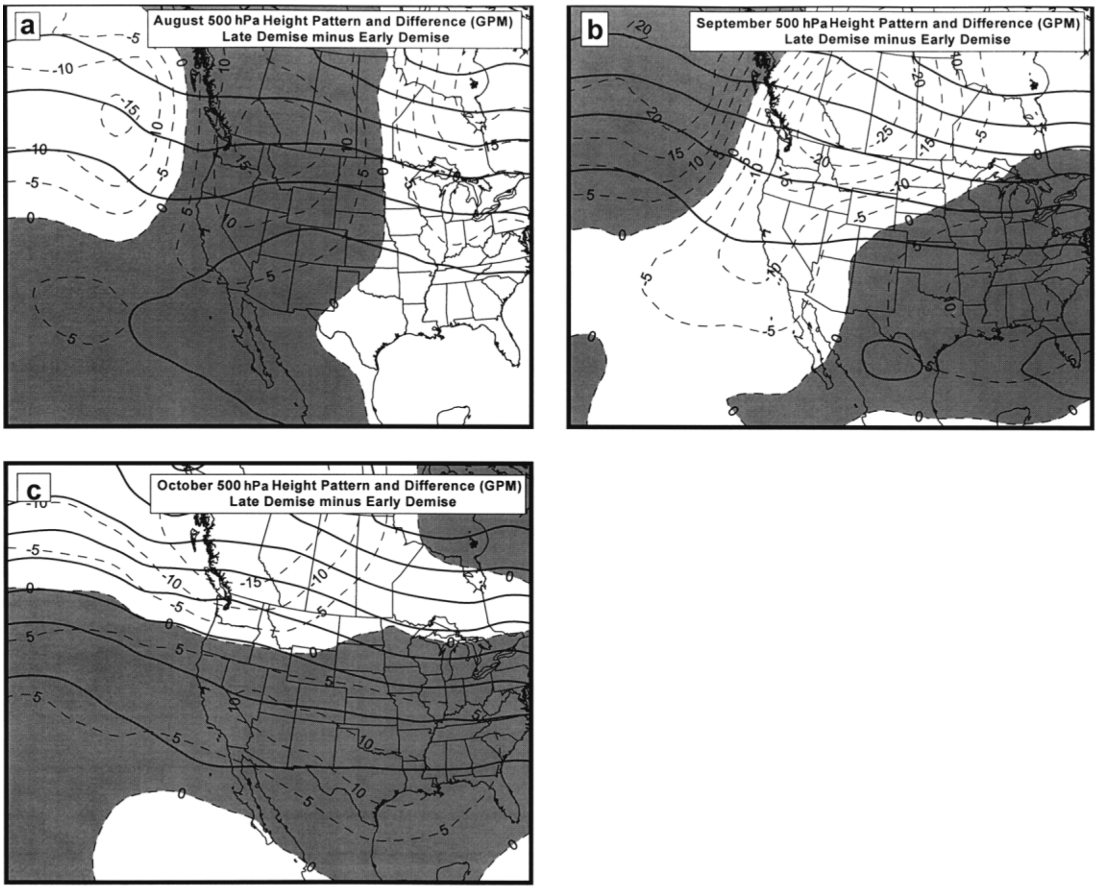

Figure 9. Mean 500 hPa height pattern (solid) and differences (dashed) between years of early and late monsoon demise for August (a), September (b), and October (c). Differences are taken as late onset minus early onset, and positive differences are shaded

Deamplifying the ridge–trough pattern across the USA may be associated with a lessened frequency of mid-latitude cyclones that pass by the monsoon region to the north and act to delay the onset of the monsoon season. The opposite scenario, an amplified ridge–trough pattern, may promote the passage of mid-latitude cyclones.

The identification of outliers in the record of annual monsoon demise dates for the period 1950 through to 2001 produced 8 years of early demises and 9 years of demise dates much later than usual. Composite differences between the 500 hPa height patterns during years of late monsoon demise and years of early demise (Figure 9) indicate an increase (decrease) in intensity and westward (eastward) shift of the August ridge (Pacific)–trough (eastern Pacific)-ridge (western North America) pattern during years of a late (early) demise (Figure 9(a)). The August pattern of a strengthened ridge during years of a late demise is typical of what is thought to be associated with a wet monsoon season. As the typical 500 hPa pattern shifts in September, so do the areas of emphasis in the difference in heights between a demise of the monsoon season that is late or early (Figure 9(b)). During September, late (early) demises are associated with height increases (decreases) in the vicinity of the Pacific ridge and southeastern North America, and height decreases (increases) along and east of the typical trough along the coastline of western North America. This seems to indicate that a late (early) demise of the season is associated with a more (less) amplified pattern and a greater propensity toward upper-atmospheric dynamics more (less) favourable for precipitation in the vicinity of the monsoon region. The monsoon region would be located between a deepening trough to the west and increased heights to the east during years of a late demise of the monsoon season. By being positioned within this favourable area for upper-atmospheric divergence, this may act to perpetuate the monsoon season over the region a bit longer than usual. By October (Figure 9(c)), the 500 hPa height pattern during late (early) demise years is marked by height increases (decreases) from the Pacific Ocean eastward to the Atlantic Ocean, indicating northward (southward) displacement of mid-latitude flow. This suggests an infrequent passage of mid-latitude systems that would inhibit the monsoon circulation during years of a late monsoon demise.

Interestingly, the height difference patterns associated with the early and late years of the onset (Figure 8) and demise (Figure 9) match well. The pattern in the shoulder month of May (Figure 8(a)) associated with onset differences matches well with that of the pattern in the shoulder month of October associated with demise differences (Figure 9(c)). In each case, the areas of emphasis are latitudinal in nature, with differences in the patterns from north-to-south across the 500 hPa height pattern. The pattern of June differences between early and late onset years (Figure 8(b)) matches well with that of September differences between early and late demise years (Figure 9(b)). In both June and September, heights are higher during early and late onset and demise years respectively in the vicinity of the Pacific ridge and southeastern North America, and lower in between across western North America. This commonality of the patterns in the differences between years of early and late occasions for the onset and demise are not apparent in July (onset) and August (demise). This may be due to the fact that July and August are the 2 months during which the monsoon is most dominant, such that the least amount of interannual variability in the 500 hPa height pattern would be expected.

3.4. Regional monsoon database

In aiming at a standardized definition of the onset and demise of the US portion of the North American monsoon season, a monsoon database was constructed using the method outlined in this paper. For each year of the period 1950–2001, several variables are created that characterize the annual monsoon season. The purpose is to provide a straightforward database that can be utilized for climatological, meteorological, and case-study analyses. First, the annual beginning and ending dates of the regional monsoon, the season length, and number of monsoon days are calculated and a historic calendar is constructed using a binary indicator of a monsoon or non-monsoon day. The mean annual regional daily dew point for the entire season and for both monsoon and non-monsoon days is also calculated as a measure of the intensity of the monsoon season.

Second, the 193 daily precipitation stations used in the methodology outlined in this paper are used to calculate the annual average monsoon precipitation across the region. Total seasonal precipitation, or that recorded on or after the start date and through to the end date, is calculated for each station and a single regional mean is calculated from all stations. The result is an annual representation of the average monsoon seasonal precipitation for a station within the monsoon region. The same calculation is used to determine the mean regional frequency of precipitation at a station within the region for each season of the 52 year record.

The historical regional monsoon season database can be accessed from the Website of the Office of the Arizona State Climatologist (http://geography.asu.edu/azclimate/), which, during each season, will include a day-to-day monitoring of the regional condition required to declare the start of the annual monsoon season. The database will be updated annually at the conclusion of the monsoon season, with the end date for the monsoon season being determined retroactively.

4. CONCLUSIONS

The North American monsoon is a summertime shift in the typical atmospheric circulation and moisture inflow across the southwestern USA–northwestern Mexico region. The criteria used to define the temporal aspect of the annual monsoon season in the southwestern USA, the specific dates of the onset and demise, are not well defined locally, and no authoritative body or set of guidelines exist for making this declaration for the region as a whole. Rather, at present, the only option for local NWSFOs is to determine criteria specific to their point location, of which only one of five regional offices has fully done so. Given that the products of the monsoon across the southwestern USA, i.e. humidity and rainfall, are regional in nature and occur on a synoptic time scale, it seems logical to define the occurrence, or the onset and demise, of the annual

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monsoon regionally. Such a definition would seem to be a better alternative to individual definitions at point locations across the region.

The study presented here outlines a method for defining the onset and demise of the regional monsoon season of the southwestern USA and assesses the results through comparisons with essentially the only local method used (Phoenix, AZ) and with atmospheric composites created from historic data. The methodology involves the establishment of thresholds of mean regional daily dew-point temperature and daily fraction of regional stations receiving precipitation. The first and last occurrences of three successive days during which both daily thresholds are met during the period June through to October constitute the beginning and ending of the regional monsoon season. These represent the first and last occurrences of moist conditions on synoptic spatial (across the region) and temporal (across a 3 day period) scales. Any day on or between the beginning and ending dates that meets both the mean regional daily dew-point temperature threshold and the precipitation occurrence threshold is categorized as a monsoon day.

Results show agreement with sample historic data derived from a similar method used locally at Phoenix, with the lone exception being a start date derived from the method outlined here that is 2 weeks earlier than that in the Phoenix record. However, the very early start date (5 June 1972) appears to be valid, given the magnitude and pattern of daily moisture and precipitation across the region and the associated atmospheric pattern. Composites of lower atmospheric synoptic-scale moisture for periods both before and after the historic dates of monsoon onset and demise clearly show a transition in regional moisture originating from the source region to the south. Descriptive statistics for the characteristics of designated wet and dry seasons show a clear dependence of seasonal precipitation on the length of the monsoon season. During the different types of season, the relative frequencies of monsoon days are similar, as are the characteristics of monsoon days in terms of humidity and precipitation, leaving season length as the primary determinant of the interannual variability in seasonal precipitation. Atmospheric anomalies (500 hPa height) associated with early/late onset and demise years generally indicate a northward shift in the mid-latitude circulation early (May) and late (October) during early onset and late demise years. However, early onset years tend, subsequently, to be associated with deamplification of the mid-latitude ridge–trough sequence (June, July), whereas late demise years tend to be associated with an amplified pattern (August, September).

Using a calendar derived from the method for determining the beginning and ending dates of the monsoon season and the occurrence of monsoon days in between, a historic monsoon season database was constructed (http://geography.asu.edu/azclimate/). Representations of the character of the annual regional monsoon season of the southwestern USA for the period 1950 through to 2001 are intended to demonstrate monsoon variability and to provide information for climatological, meteorological, and case-study analyses of the southwestern monsoon.

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