Summertime Convective Storm Environments in Central Arizona: Local Observations

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ABSTRACT

The daily evolution of local surface conditions at Phoenix, Arizona, and the characteristics of the 1200 UTC sounding at Tucson, Arizona, have been examined to determine important meteorological features that lead to thunderstorm occurrence over the low deserts of central Arizona. Each day of July and August during the period 1990–95 has been stratified based upon daily mean, surface moisture conditions at Phoenix, Arizona, and the occurrence of afternoon and evening convective activity in the Phoenix metropolitan area. The nearest operational sounding, taken 160 km to the southeast at Tucson, is shown to be not representative of low-level thermodynamic conditions in central Arizona. Thus, Phoenix forecasters' ability to identify precursor conditions for the development of thunderstorms is impaired. On days that convective storms occur in the Phoenix area, there is a decrease in the diurnal amplitude of surface dewpoint changes, signifying increased/deeper boundary layer moisture. This signal is very subtle and may not have much forecast utility. Additionally, it is found that surges of moist air from the Gulf of California do not occur frequently during the 36–48 h immediately prior to thunderstorm events in the Phoenix area. It is shown that the 1200 UTC Tucson wind profile has a significant northerly flow in low levels on moist days when storms do not occur in the Phoenix area. The forecaster needs information on the local temperature and moisture profile to assess the potential for thunderstorms in the Phoenix area. However, routine upper-air observations are unavailable. Steps are being taken to obtain morning soundings in Phoenix, and the improving capabilities of satellite-derived thermodynamic data and mesoscale models may also provide the forecaster critical information in the future. The findings, although specifically developed for the Phoenix area, may be relevant to thunderstorm forecasting in many regions of the interior West.

1. Introduction

Arizona lies at the northern periphery of a large area in Mexico that experiences a distinct period of summer raininess. This Mexican monsoon, described by Douglas et al. (1993), affects a large portion of southwestern North America encompassing western Mexico, Arizona, and New Mexico. Much of the region affected by the monsoon experiences the bulk of its annual precipitation during the summer period. The monsoon influence is greatest over western and northwestern Mexico and extends into southeastern Arizona where average precipitation during July, August, and September exceeds 50% of the mean annual total. The Phoenix metropolitan area receives approximately 40% of its mean annual rainfall during the monsoon period. Douglas et al. (1993) argued that the Arizona summertime precipitation singularity (e.g., Bryson and Lowry 1955) reflects the northern extension of the summer precipitation maximum of the Mexican monsoon. In this study, the warm season precipitation singularity over the southwest United States and northwest Mexico will simply be referred to as the *monsoon.* Adams and Comrie (1997) provide a comprehensive overview of monsoon-related literature.

During the monsoon period, thunderstorms are an almost daily occurrence over portions of western Mexico, Arizona, and New Mexico. Satellite infrared imagery (e.g., Douglas et al. 1993; Gourley et al. 1998) indicates that during July and August deep convection occurs very frequently over Mexico west of the Continental Divide. The Mogollon Rim, White Mountains (refer to map in Fig. 1), and southeastern Arizona also experience frequent convection, whereas thunderstorms are relatively rare over the desert regions of the state. The large spatial variability of deep convection over Arizona (see López et al. 1997) is directly related to the highly complex terrain of the state.

In the past, thunderstorms in the southwestern United States have been of relatively minor significance due the region's relatively sparse population, and the char-

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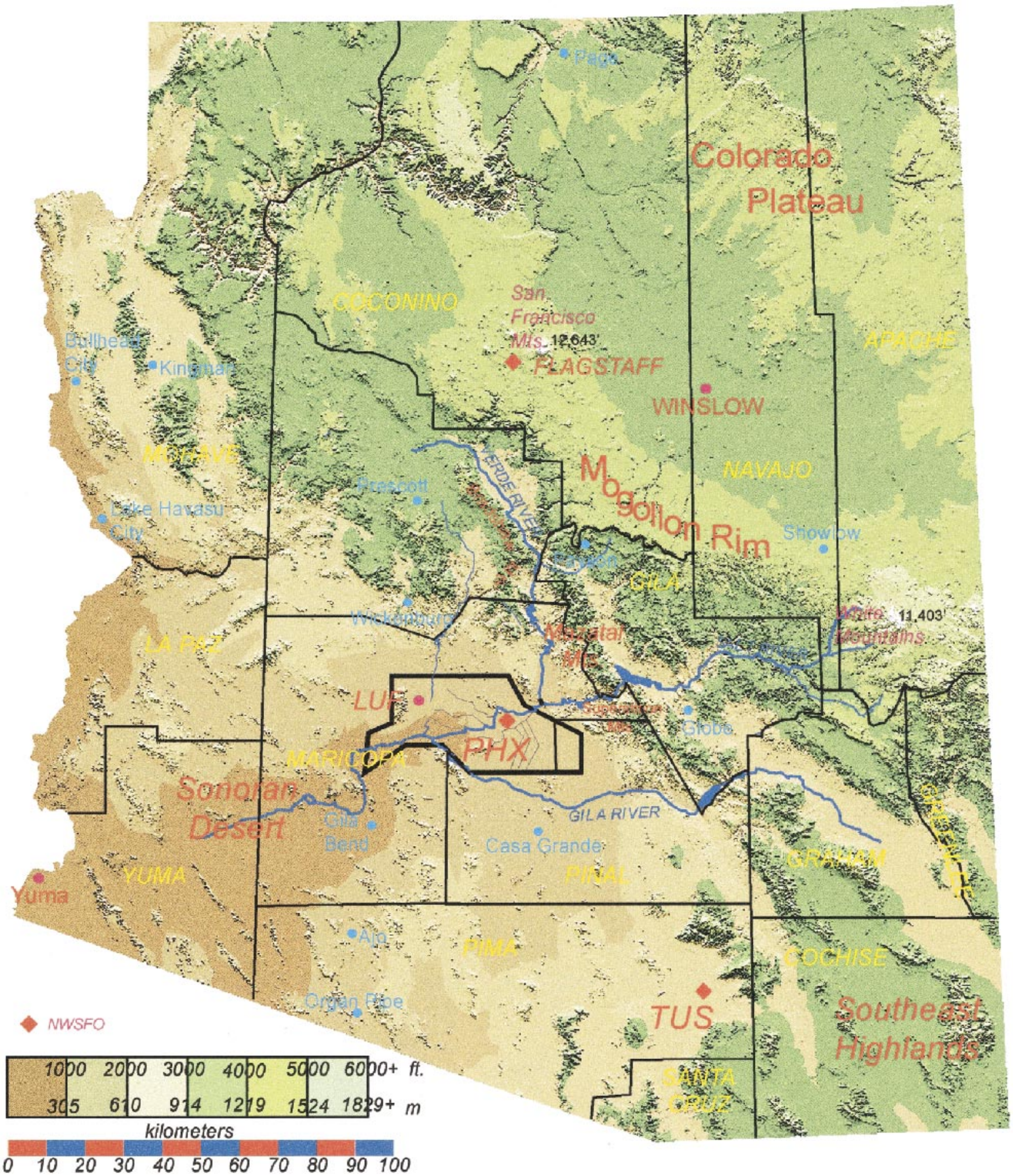

FIG. 1. Arizona topographic map, major geographic features, counties, cities, and NWSFO locations. The bold outline surrounding Phoenix encompasses the Valley.

acter of the monsoon environment of Arizona remains largely undocumented. However, in recent years this region, especially the Phoenix metropolitan area, commonly referred to as ''the Valley,'' has seen rapid population growth. Even though the impact of thunderstorms remains small over much of Arizona, they can have a significant social and economic impact in the Phoenix metropolitan area.

For example, water and power providers, such as the Salt River Project (SRP), require accurate forecasts of the daily high temperature (see Dempsey et al. 1998). The occurrence of thunderstorms, especially during the afternoon (i.e., during peak power production and demand) in and around the Valley can dramatically reduce the high temperature or cause evening temperatures to plummet rapidly (McCollum et al. 1995). In either case, forecasted power production exceeds power demand resulting in expensive losses. Electric service interruptions caused by downed lines and/or poles, damaged circuits, and faults (i.e., power outages lasting more than a few seconds) resulting from strong damaging winds, heavy rainfall, frequent lightning, and other severe weather often accompany monsoonal thunderstorms.

It is well known that forecasts, watches, warnings, and model predictions verify poorly during the warm season in Arizona (Dunn and Hotel 1994a,b; Maddox et al. 1995; McCollum et al. 1995). Hence, the Phoenix area is the largest metropolitan area in the western United States with a significant summertime thunderstorm forecast and warning problem. Two important questions related to the thunderstorm forecasting problem concern both operational forecasters and researchers alike: 1) What conditions lead to summertime thunderstorms in central Arizona, especially in the Valley? 2) Are *operational surface and sounding data* useful in any way to determine conditions favorable for convective storms over Arizona's south-central desert areas? This study addresses these questions.

2. Background and study methodology

a. Arizona monsoon thunderstorms

Compared to much of the rest of the United States, the weather in Arizona is generally benign much of the year (Smith and Gall 1989). During the monsoon the rugged, mountainous terrain of Arizona (see Fig. 1) typically experiences frequent thunderstorm activity (Hales 1977; Watson et al. 1994b; López et al. 1997; Dempsey et al. 1998). Deep convection is most frequent over and to the south and west of the higher elevations of the White Mountains, Mogollon Rim, and the southeast Arizona highlands. Each of these features has steep slopes that face to the south and west, thus providing effective orographic forcing for vertical motion and the development of thunderstorms. The low deserts, however, experience significant storm or rainfall events more intermittently during the monsoon.

Across the northern extent of the Gulf of California, the Sonoran Desert, and the lower Colorado River basin, thunderstorms are infrequent. Douglas and Li (1996) used special upper-air data to show that in the afternoon over the low deserts (see Fig. 1) there is large-scale subsidence caused by diffluent, low-level, upslope winds. Many drainage basins in the interior of the West may be affected by similar diurnal flow regimes that modulate the local occurrence of thunderstorms, for example, the Snake River Plain of Idaho and the Rio Grande Valley of New Mexico.

Several investigators (Balling and Brazel 1987; Hales 1972, 1977; Watson et al. 1994b) have shown that Arizona experiences a pronounced and complex diurnal regime in summertime precipitation and thunderstorm activity. During the late morning through early afternoon, thunderstorms are typically confined to the highest terrain. Over the central and eastern mountains there is a pronounced midafternoon maximum of thunderstorm activity directly attributable to diurnal heating and local mountain–valley circulations. Thunderstorm activity often propagates west and southward in a quasi-continuous fashion down the topography gradient and *occasionally* enters the lower deserts by early evening. It appears likely that both drainage winds and outflow from storms along the higher terrain converging with hot, moist, and unstable air over the deserts is critical for thunderstorm initiation over the Valley.

Very uneven population distribution across the state results in a surface observation network biased toward major population centers. Hence, there is poor sampling of surface conditions across many areas of the state. In addition, the complex terrain of the state results in surface observations being, at best, representative of relatively small areas. The nearest upper-air sounding sites to the Valley are located at Tucson, Flagstaff (relocated from Winslow in September of 1995), and Miramar Naval Air Base in San Diego, California. The Flagstaff (Winslow) site at an elevation of 2137 m (1505 m) is (was) at much greater elevation than Phoenix, which has an elevation of 342 m. The Flagstaff site is located in a region of increased summer precipitation with widespread conifer forests. The San Diego site with an elevation of 147 m is located near the coast and is covered by cool, stable marine air from the eastern Pacific through most of the warm season. Tucson, which is located 160 km to the south-southeast of Phoenix, is the only one of these sites that experiences environmental conditions that might be considered ''representative'' of the Phoenix region.

Tucson, at an elevation of 779 m, is 447 m higher than Phoenix. Tucson is also much closer to elevated terrain than the Valley and, thus, closer to many sources of orographic forcing (see Fig. 1). The Valley is located in the Sonoran Desert, whereas Tucson lies at the margin between the Sonoran Desert and the higher grasslands and ''sky islands'' of extreme southeastern Arizona. Because of this, the summertime precipitation climatology of the Valley is much different than that of southeastern Arizona. Figure 2 shows total number of events occurring in July and August at Phoenix and Tucson with hourly precipitation observations of 0.01 in. or more and thunderstorm observations with hourly precipitation of 0.01 in. or more from 1961 to 1990. Tucson experiences a peak in precipitation and thunderstorm activity 3 h prior to the peak in Phoenix, with approximately

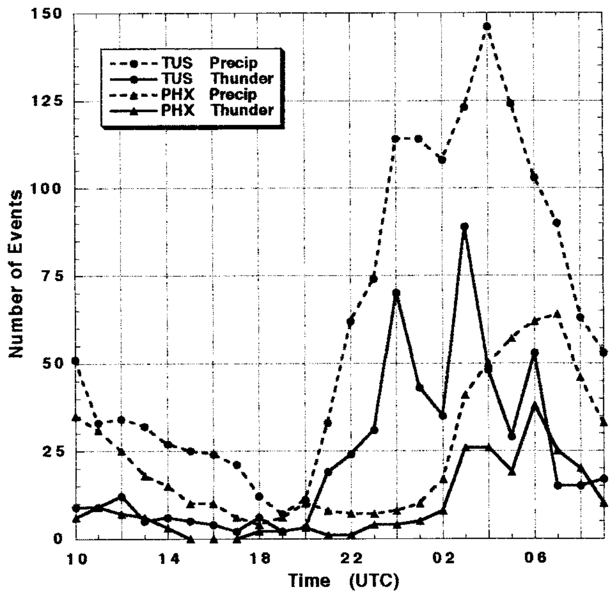

FIG. 2. Total number of events occurring in Jul and Aug at PHX and TUS with hourly precipitation observations of 0.01 in. or more and thunderstorms observations with hourly precipitation of 0.01 in. or more (data provided by D. Bright, NWS, Tucson).

250% more reports of thunder between 2100 and 0900 UTC. In addition to the occurrence of many more events in Tucson than in Phoenix, the earlier Tucson maximum of precipitation and thunderstorm events suggests that the 0000 UTC sounding at Tucson may often be contaminated by local storm activity.

b. Data and analysis methods

The region of primary interest in this study is indicated in Fig. 1 by the bold outline surrounding Phoenix. This area is of roughly constant terrain elevation. Although a few small orographic features, such as Camelback Mountain at 824 m, are in the study region, elevations are generally 300 m in the southwest Valley and gently slope to approximately 500 m in the eastern and northeastern Valley.

Six years (1990–95) of WBAN (i.e., weather bureau, air force, and navy) hourly surface observations for Phoenix Sky Harbor International Airport (PHX) and Luke Air Force Base (LUF) were obtained from the National Climatic Data Center (NCDC). The official National Weather Service (NWS) surface observation for the study region is taken at PHX (elevation 342 m), which is located in the east-central Valley just to the southeast of downtown Phoenix. LUF (elevation 336 m) is located in the extreme northwestern Valley. The ceiling height, sky condition, visibility, weather, obstruction to vision (including thunderstorm intensities, type and intensity of precipitation, and various obstructions to vision such as blowing dust and sand), sea level pressure, dewpoint temperature, wind direction and speed, station pressure, both dry- and wet-bulb temperatures, relative humidity, and clouds and obscuring phenomenon were all included in the surface dataset.

During March 1994 the NWS commissioned their Automated Surface Observing System (ASOS) as the official weather observation for Phoenix. Manual observations were taken for the first four years of this study at a site approximately a mile from the current site. Some systematic differences appear to exist between data collected at the manual and automated (ASOS) sites (J. Skindlov, Salt River Project 1996, personal communication). On average the ASOS recorded a maximum (minimum) temperature 1°F (2°F) below the manual site. Dewpoint temperatures measured at the ASOS site during July of 1993 tended to be as much as 2°F lower during the afternoon on average. Because of the short record, no attempt has been made to correct the 1994 and 1995 data. However, future studies will have to address this problem.

All days of July and August were studied for the years 1990–95. This period captures the primary summer monsoon thunderstorm season and avoids the transitory periods of June and September. A *day* has been defined (based on the PHX thunderstorm climatology; see Fig. 2) to be the 24-h period beginning just after 0900 UTC (0200 MST). The surface observations were examined for two 12-h periods. The first period covers the Phoenix thunderstorm *minimum* during the early morning through early afternoon (0900–2100 UTC), with the second spanning the period of *maximum* thunderstorm activity during the late afternoon and evening (2100–0900 UTC).

Widespread convective events in the Valley often have a profound effect on the following day's boundary layer conditions (Dempsey et al. 1998). Days on which precipitation and/or convective storms occurred in the Valley between 0900 and 2100 UTC were considered ‘‘contaminated'' and are not considered further. Days on which stratiform precipitation was reported without any indication of convective storms in the Valley were not considered. *Thus, the focus is on afternoon or evening thunderstorms and their undisturbed, precursor conditions.* It is this situation that poses the greatest forecast challenge.

Subjective analysis of the PHX surface observations for all days of July and August 1990–95 indicated that 73 of the 372 days were contaminated. The remaining 299 days are referred to as *study days.* Each study day was further classified based on the PHX daily mean surface dewpoint temperature, precipitation, and convective storm activity in the Valley.

To examine the relationship between the occurrence of thunderstorms in the Valley and surface moisture, study days were classified as either *monsoon days* (MDs) or *dry days* (DDs) days using the average daily (24-h period beginning at 0900 UTC) dewpoint at PHX.

Forecasters in Phoenix identify the onset of the monsoon by the presence of average dewpoints of 55°F for

TABLE 1. Criteria used to define the various event categories and number of days on which each event category occurred. SFC indicates the number of days on which PHX surface observations were available, and UA indicates the number of 1200 UTC TUS upper-air soundings used in each event category.

Event categories/number of days	Criteria
PHX Surface observations contaminated—73 days	Precipitation or convective storms in the Valley between 0900 and 2100 UTC Precipitation in the Valley without convective storms between 2100 and 0900 UTC
TUS Upper-air sounding contaminated—68 days	1200 UTC Tucson UA sounding contaminated by precipitation or convection
Study days SFC: 299 UA: 231	All uncontaminated days of Jul and Aug 1990–95
Dry days SFC: 126 UA: 112	Study days with PHX average daily dewpoint <55°F
Monsoon days SFC: 173 UA: 119	Study days with PHX average daily dewpoint ≥55°F
Convective storm days SFC: 58 UA: 38	Monsoon days on which • observer reports thunder at PHX or LUF • storm damage in the Valley • cloud-to-ground lightning in the Valley • hail reported in the Valley • severe storm verified in the Valley between 2100 and 0900 UTC
No-storm days SFC: 115 UA: 81	Monsoon days without precipitation or convective storms in the Valley

at least three consecutive days. The 3-day duration should indicate that a large-scale, monsoon flow regime has become established. This eliminates many false alarms that would otherwise occur in early June associated with frontal passages and other transitory features in the westerlies. Schmidli (1986) defines a *monsoon day* for the Phoenix area as any day during the monsoon period for which the average of the hourly dewpoint temperature equals or exceeds 55°F. Schmidli's definition has been applied to the PHX surface data to define MDs (173). Those days with a daily mean dewpoint less than 55°F were classified as DDs (126). Table 1 illustrates the event categories.

Observations for PHX are used as the primary surface data for three reasons. First, Phoenix forecasters employ observations from Sky Harbor Airport to define the onset of the monsoon. Second, Sky Harbor is situated in the central portion of the Valley. Third, NWS forecasts for the Valley are verified using Phoenix data from Sky Harbor.

All available observations for each MD were examined to determine if late afternoon and evening (2100–0900 UTC) convective storm events occurred in the Valley, and then each MD was classified as either a convective storm day (CSD) or a no-storm day (NSD). The terminology *convective storms* is used in lieu of thunderstorms since indicators other than just reports of audible thunder were used in determining if storms were present in the Valley (see Table 1). Thunderstorms are defined to occur when an observer at either PHX or LUF hears thunder. Monsoon days on which thunder was observed at either PHX or LUF between 2100 and 0900 UTC are CSDs. Furthermore, days on which thunder was not observed at either station, yet convective storms were present in the Valley, were also defined as CSDs. To aid in determining CSDs, *Storm Data* (NCDC 1990–95) and Phoenix NWS *Local Storm Reports* were examined for all six years. Any damage owing to high winds, lightning, or flash flooding in the Valley on MDs was considered a result of thunderstorms. Additionally, National Lightning Detection Network data obtained from Global Atmospheric Incorporated were examined for occurrences of cloud-to-ground lightning in the Valley. Severe thunderstorm days were CSDs, and hail of any size indicated a CSD. Warnings issued by the Phoenix National Weather Service Forecast Office (NWSFO), *Local Climatological Data Monthly Summaries*, and *Local Storm Reports* were examined to verify the occurrence of convective storms in the Valley. No-storm days include all days on which neither convective storms nor any type or intensity of precipitation were indicated. Of these 173 MDs, 58 CSDs and 115 NSDs were identified. Thus, for the study period, only about one-third of the uncontaminated, that is, ''typical,'' summer MDs experienced in Phoenix actually had convective storm events late in the day.

Hourly mean surface observations were computed for DDs, MDs, NSDs, and CSDs. The PHX surface conditions were compared for different type days to determine similarities and differences. Subjective comparisons, as opposed to rigorous statistical tests, were adequate to highlight any potential forecast utility. Only those observations prior to the first indication of a convective storm (e.g., an abrupt wind shift and/or increase, rapidly rising surface pressure, rapidly falling temperature, thunder, or precipitation) on CSDs were utilized in the calculations. All observations were considered if no appreciable impacts resulting from thunderstorms occurred at the PHX observation site. Convectively contaminated observations are not included in the CSD hourly averages, which reduces the sample size of surface observations by evening.

Phoenix forecasters must rely heavily on the operational Tucson 1200 UTC sounding in making their forecasts of afternoon and evening storm probabilities. Since the Tucson 0000 UTC data are often contaminated by convection, the 1200 UTC upper-air soundings were examined to determine what similarities and differences exist in the *Tucson* data for the different classifications of *Phoenix* summer days. Tucson (TUS) rawinsonde data were obtained from a copy of the National Oceanic and Atmospheric Administration/Forecast Systems Laboratory rawinsonde database (Schwartz and Govett 1992) for 1200 UTC. Mean soundings (data were averaged at 25-mb increments) were computed for each type of day to examine thermodynamic and wind characteristics.

Individual 1200 UTC Tucson soundings were carefully examined for each study day to eliminate soundings contaminated by light rain or mesoscale downdrafts resulting from nighttime and early morning thunderstorm activity in the Tucson area. Surprisingly, 68 of the 299 study days were found to have 1200 UTC soundings at Tucson contaminated by morning precipitation, convective storms, or mesoscale downdrafts. These soundings could not be considered representative of the low deserts (i.e., the Valley) and were eliminated from the upper-air analyses. The frequent occurrence of late night and early morning showers and outflows in the Tucson area means that forecasters, as well as operational prediction models, often have no upper-air sounding representative of the large-scale environment over south and central Arizona.

3. Observations by type of day

July and August represent the principal monsoon season in Arizona; however, this period is marked by intermittent periods of dry conditions atypical of the warm season convective storm environment (Carleton 1986; Watson et al. 1994a). Examination of the data for the different categories of days (see Table 1) is essential to assess the storm environment and the usefulness of the current operational observations (i.e., the PHX surface data and the 1200 UTC Tucson upper-air sounding). The following sections describe the mean daily evolution of the surface conditions at PHX, and the characteristics of the 1200 UTC soundings taken at Tucson for DDs, MDs, CSDs, and NSDs to illustrate the important meteorological attributes of the different classifications of days.

a. Dry days

Approximately 30% of all days in July and August of the study period have dry, essentially nonmonsoon conditions. Several years of the study period (i.e., 1993 and 1994) were unusually dry at PHX, so this percentage of DDs may be higher than during the ‘‘typical’’ year. Regardless, it is clear that the influence of the monsoon circulation is quite intermittent over central Arizona and that a large number of days during the summer do *not* pose a thunderstorm forecasting problem for the Valley. At 1200 UTC on DDs, the mean PHX dewpoint is 48°F (Fig. 3a). However, there is considerable variability.

Local orographic effects on DDs (Fig. 3b) dominate surface wind direction. With the heating of the higher terrain to the north and east of PHX, the winds veer to the west-southwest shortly after local noon. Throughout the afternoon and early evening the surface winds are westerly. A rapid shift to northeasterly at 0900 UTC occurs with drainage flows from higher terrain. In the afternoon mean winds speeds are slightly higher than in the morning owing to afternoon turbulent mixing in the boundary layer. The high terrain to the east and northeast of the Valley clearly plays a major role in determining the surface wind at PHX. Surface temperatures show a diurnal pattern of large amplitude.

The mean 1200 UTC Tucson sounding for the DDs (see Fig. 4) shows substantially lower moisture content (in comparison to MDs). The subsequent lack of convective activity on these days is due to the advection of dry air into Arizona from the eastern Pacific. Deep westerlies exist from 850 mb up to the tropopause. This large-scale flow regime is typical of that of May and June, when the subtropical high is suppressed equatorward, bringing the region under increased subsidence. During the summer, strong short waves translating in the westerlies at more northern latitudes can occasionally force the subtropical high southward bringing dry Pacific air into the state, causing the intermittent nature of the monsoon in Arizona.

Intense daytime heating and the presence of the nocturnal residual layer typically results in a deep (i.e., extending to between 700 and 500 mb) boundary layer over much of the state during the afternoon. As mixing occurs during the late afternoon, dry air with the midtroposphere westerlies is entrained into the boundary layer thus stabilizing the lower troposphere with respect to moist convection (Fig. 4). The mean dewpoint temperature profile throughout the lower and middle troposphere is 5°–9°C less than that for all monsoon days. No significant difference exists in vertical temperature profiles at Tucson throughout the troposphere between DDs and MDs. The considerably drier lower-tropospheric conditions give a mean layer mixing ratio of 7.3 g kg^{-1} in the first 500 m above ground level, and stable conditions. There is no CAPE in the mean 1200 UTC Tucson sounding for DDs.

b. Monsoon days

Surface conditions for the 173 MDs at PHX reflect the higher moisture content of the lower troposphere (Fig 5a). The mean dewpoint at 1200 UTC on monsoon days is nearly 63°F. As mixing occurs during the day-

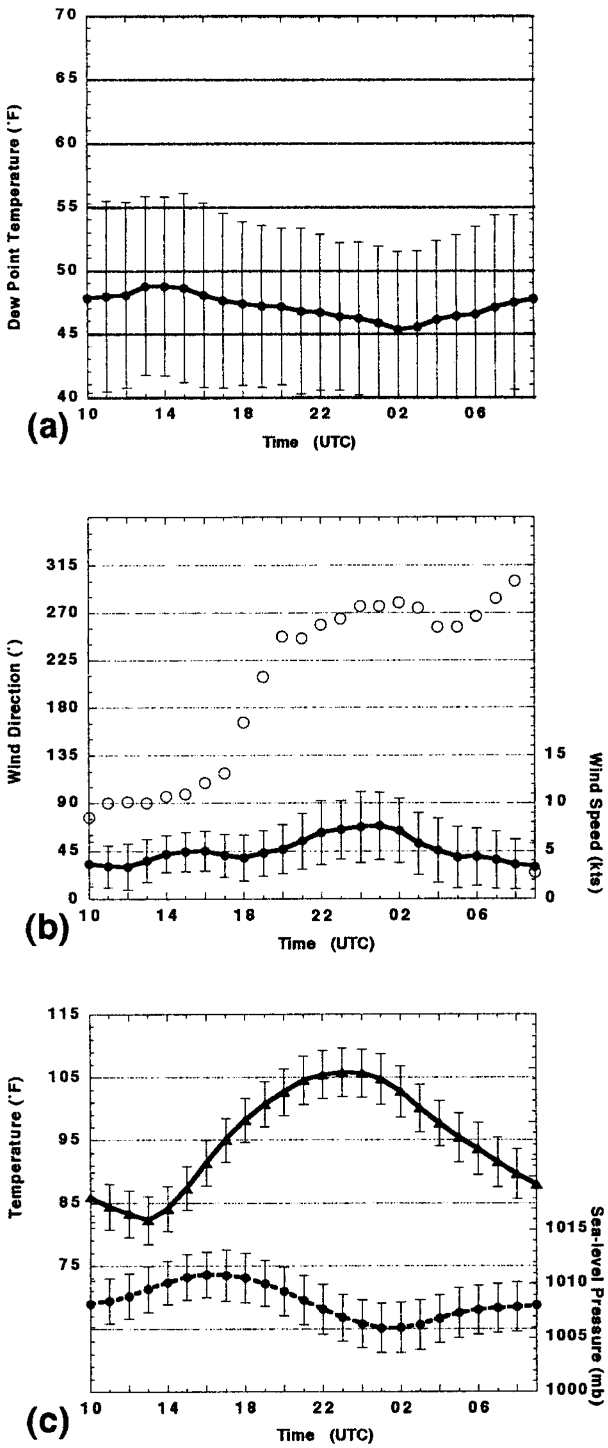

FIG. 3. PHX mean (a) dewpoint temperature (°F), (b) wind direction (°) and speed (kt), (c) sea level pressure (mb), and temperature (°F) during the 126 dry days. Bars are ±1 standard deviation.

time, mean dewpoint temperatures decrease to approximately 59°F by 0200 UTC. The mean hourly dewpoint is generally 15°F greater on MDs compared to DDs! This is a dramatic difference between monsoon and dry days (note the standard deviations of the mean dewpoint for each classification do not overlap), strongly indicating the contrast between these two different synoptic situations. On both classifications of days, winds veer from easterly downslope winds to upslope wind between 1700 and 1900 UTC (Fig. 5b). After 0100 UTC winds begin to back toward the south on MDs. The mean winds after 2100 UTC on MDs include the affects of the thunderstorm events and thus cannot be considered completely representative of the large-scale flow.

The increased low-level moisture decreases the amplitude of the diurnal temperature change. In the late afternoon temperatures are on average 1.5°F cooler than the mean for DDs, and morning temperatures are slightly warmer (Fig. 5c). Dramatically increased surface moisture and only slightly cooler afternoon temperatures suggest that more unstable conditions exist over the Valley on MDs. However, the lack of routine operational, upper-air data in central Arizona precludes precise determination of the actual boundary layer conditions over the Valley.

The increase in convective activity across the state on MDs is associated with southeasterly midtropospheric flow as indicated by the Tucson sounding (Fig. 4). In the mean there is a deep layer of 3–8 kt east to east-southeasterly flow extending from the top of the morning residual layer (i.e., 700 mb) to approximately 450 mb. Moisture is carried by this flow around the subtropical anticyclone and results in moistening of the midlevels. Dewpoint temperatures in the 700–400-mb layer are about 5°C greater throughout this layer than on dry days. Midlevel moisture is important in moderating the convective potential in Arizona. Since the depth of the afternoon boundary layer over the higher terrain grows to depths between 700 and 500 mb, air at midlevels is commonly within the mountain boundary layer. Hence moist (dry) air at midlevels would tend to increase (decrease) the afternoon convective potential over the mountains. Over the deserts, the deep afternoon boundary layer will not entrain very dry air from above when midlevel moisture is present; thus, whatever CAPE is present, or develops, for boundary layer parcels is maintained on MDs. The mean 1200 UTC Tucson sounding for monsoon days shows that in addition to the increased midlevel moisture, low-level dewpoint temperatures are also higher by about 6°C when compared to the profile for DDs. No significant difference exists in the lower-tropospheric temperature profile between the mean for DDs and MDs.

The mean 1200 UTC Tucson sounding for MDs has slight potential instability. Computation of CAPE, using a mean parcel for the first 500 m above the surface, gives a mean value of 146 J kg^{-1}. Since the 1200 UTC Tucson sounding must be used operationally to evaluate stability conditions in the Valley, the fact that in the mean the 1200 UTC TUS sounding is potentially unstable for *all monsoon days in Phoenix* demonstrates

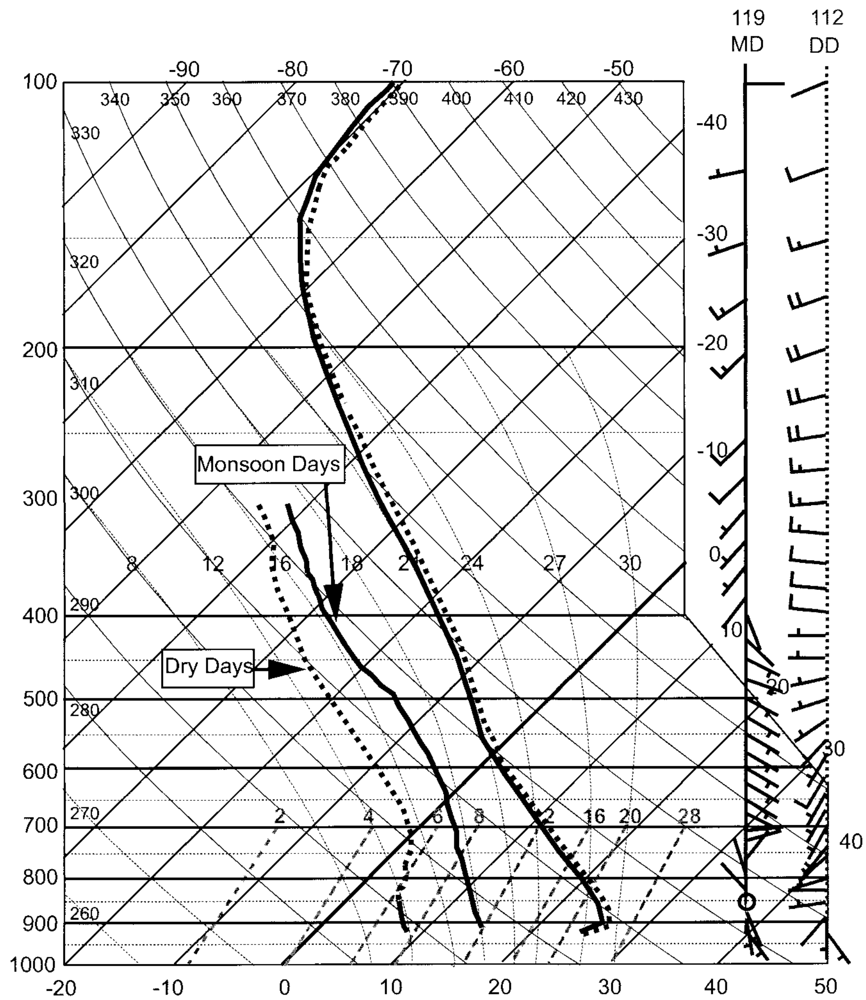

FIG. 4. Average TUS 1200 UTC skew *T*–log*p* sounding plot for 119 monsoon days (solid) and 112 dry days (dashed). Winds are 5 m s^{-1} for full barbs and 2.5 m s^{-1} for half barbs.

the difficulty of correctly ascertaining convective potential in the Valley.

c. NSDs versus CSDs

Prior to 2100 UTC there are few significant differences in the PHX mean surface observations between NSDs (Fig. 6) and CSDs (Fig. 7). After sunrise the differences in dewpoint between CSDs and NSDs increase. The dewpoint at 0200 UTC is 1°–2°F greater than NSD on average (i.e., there is less difference on CSDs between the morning and afternoon dewpoint opposed to NSD observations). The higher dewpoints in the afternoon result from increased/deeper boundary layer moisture.

It is difficult to determine if the higher surface moisture is a reliable signal for forecasters, since the number of uncontaminated observations decreases considerably in the late afternoon. Perturbations from the mean diurnal NSDs values 8 h prior to 3 h after the onset of a CSD event were calculated to determine if significant differences exist between the typical NSD and CSD surface observations. The onset of a CSD event was defined to be the hour in which a noticeable affect (e.g., a sudden temperature drop or dramatic wind shift) from convective storms in the Valley was indicated in the PHX surface observations. Data from CSDs that did not affect conditions at PHX were used. There is no significant difference between CSDs and NSDs in PHX surface temperature and sea level pressure for 8 h prior to an event in the Valley (Fig. 8). However, beginning about 8 h prior to an event in the Valley, surface dewpoints remain elevated relative to NSDs. In the mean, convective mixing (i.e., surface dewpoints decreases) still occurs in the afternoon, but the amplitude of the diurnal dewpoint change is slightly smaller on CSDs (Fig. 8). After the onset of an event, there is dramatic cooling, a resulting pressure rise, and dewpoints rise, in response to precipitation and evaporation in the boundary layer.

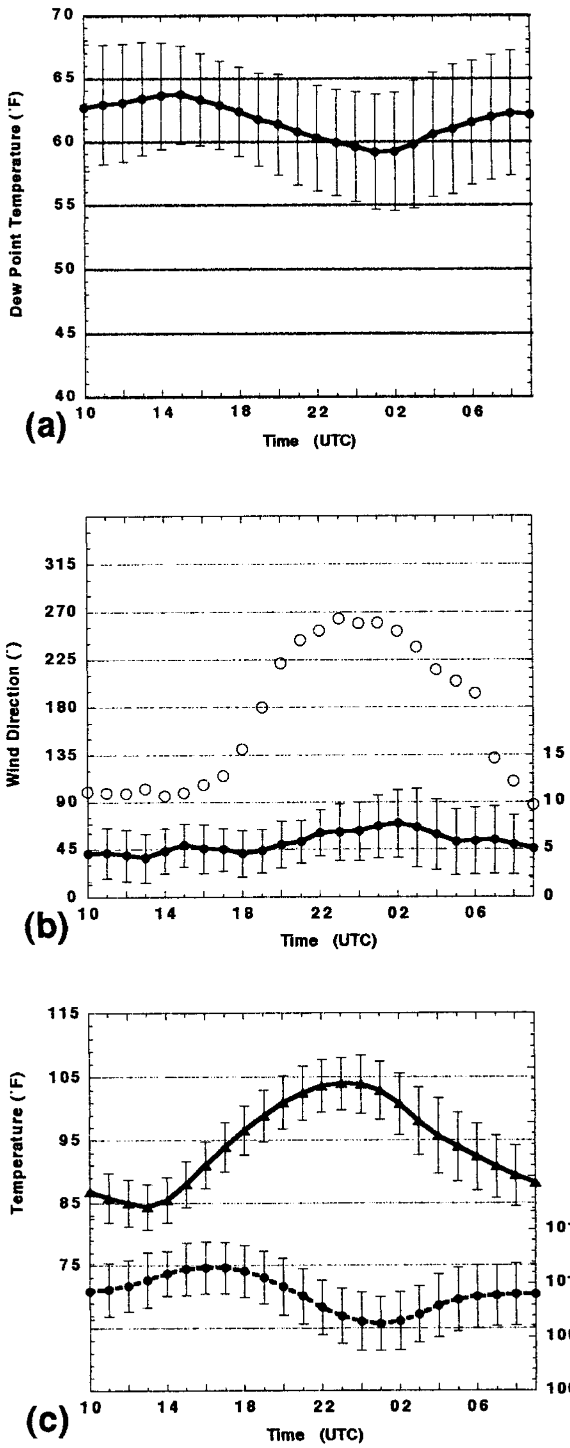

FIG. 5. As in Fig. 3 except for the 173 MDs.

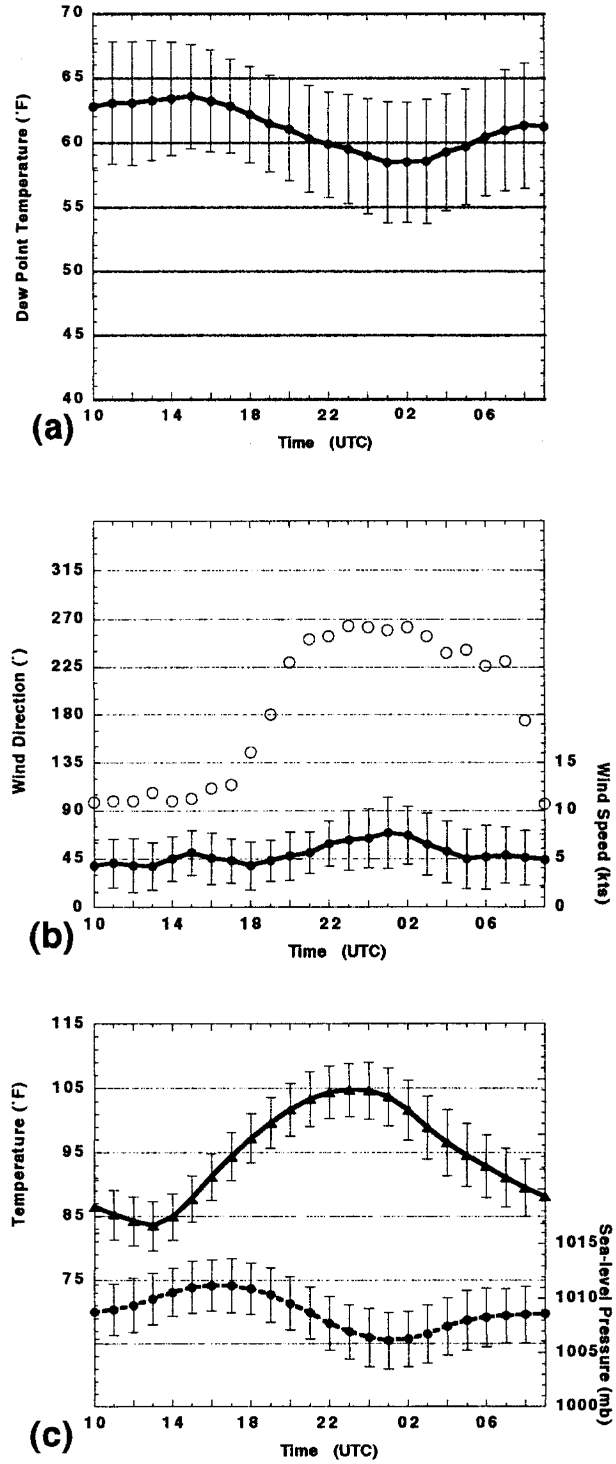

FIG. 6. As in Fig. 3 except for the 115 NSDs.

Thermodynamically, there is *no* significant difference between CSDs and NSDs in the 1200 UTC TUS sounding (Fig. 9). The CSDs are only slightly more unstable (e.g., mean CAPE in the morning on NSDs is 50 J kg^{-1} vs 277 J kg^{-1} on CSDs) due to slightly increased mixing ratios. Thus, the 1200 UTC Tucson sounding provides little meaningful thermodynamic information to allow PHX forecasters to assess the day-to-day convective potential in the Valley.

On a more positive note, examination of the vertical

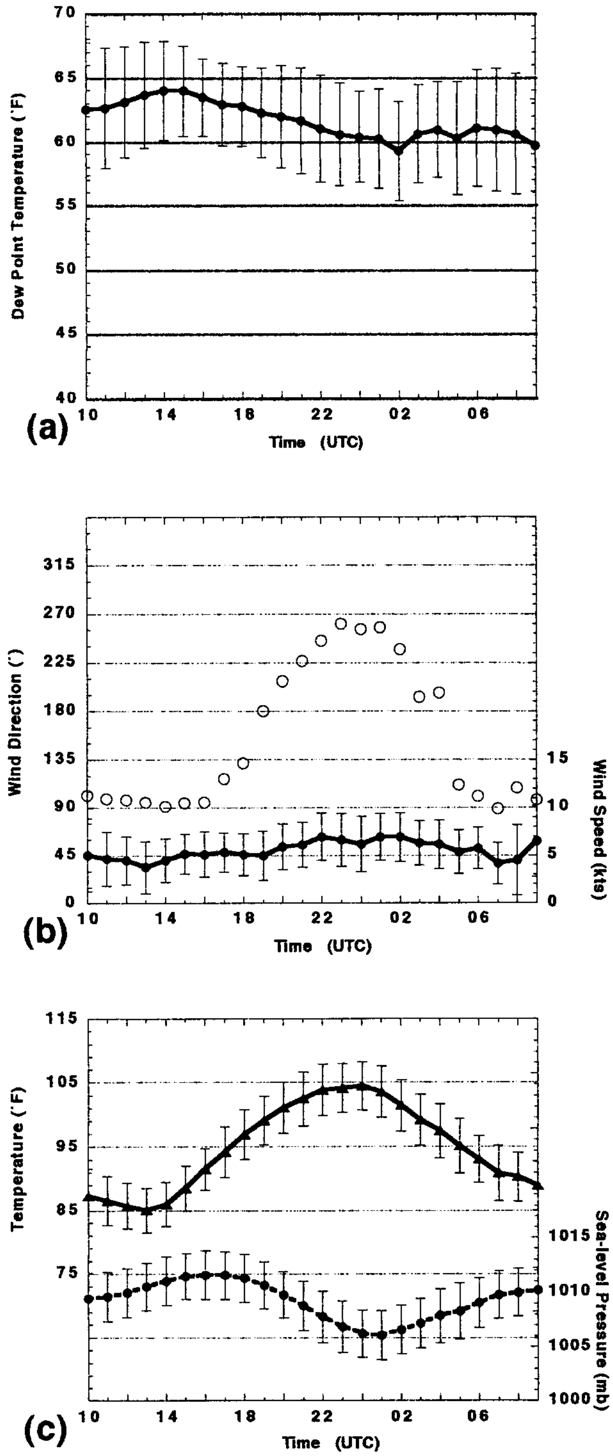

FIG. 7. As in Fig. 3 except for the 58 CSDs.

wind profiles suggests that useful forecasting information for the Valley may be obtained by examining the low- and midlevel winds (Fig. 9). Above 700 mb there is a layer of relatively strong east-southeasterlies extending up to 375 mb, which, as discussed earlier, could

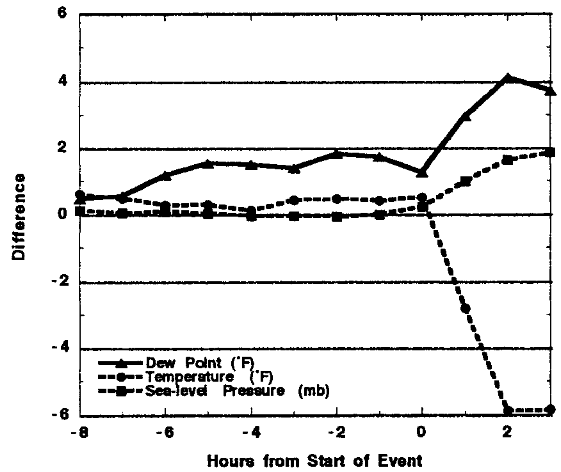

FIG. 8. Mean PHX temperature (°F), dewpoint temperature (°F), and sea level pressure (mb) perturbations from the no-storm day average surface conditions for 8 h prior and 3 h past the onset of an event at PHX on convective storm days.

aid in moistening of midlevels. This layer is deeper than that found on NSD and wind speed is approximately 5 kt greater. The stronger winds in this deeper layer aid in movement of storms off the higher terrain into the lower deserts. The stronger winds suggest tightening of the midlevel pressure gradient, possibly reflecting the passage of disturbances in the easterlies.

Additionally, above the nocturnal boundary layer up to 700 mb there are pronounced northwesterly winds at Tucson on Phoenix NSDs. Northwesterly winds in this layer may indicate that the large-scale circulation is advecting dry air from the north and west over the low deserts, especially the Valley. This will cause drying in the afternoon boundary layer over the low deserts and subsequently decrease the convective potential in the Valley. There are two possible explanations for the unusual low-level 1200 UTC northwest winds at Tucson: (a) the low-level, northwest Sonoran anticyclone (see Douglas and Li 1996) is stronger on PHX NSDs, and (b) the lower-tropospheric thermal low over the California deserts has weakened and a pressure trough to the east of Tucson is determining the flow in this layer. The first situation would tend to advect higher moisture from the Sonoran Desert and Gulf of California into the low deserts while the second situation would tend to advect dry, continental air over the Valley. Thus, the second possibility seems most plausible, since there is a decrease in deep convection across most of the lower deserts on NSDs. Alternatively, the difference may also arise as a consequence of the limited number of years evaluated.

d. Moisture surges

A number of studies (e.g., Hales 1974; Brenner 1974; Douglas 1995; McCollum et al. 1995) have shown that

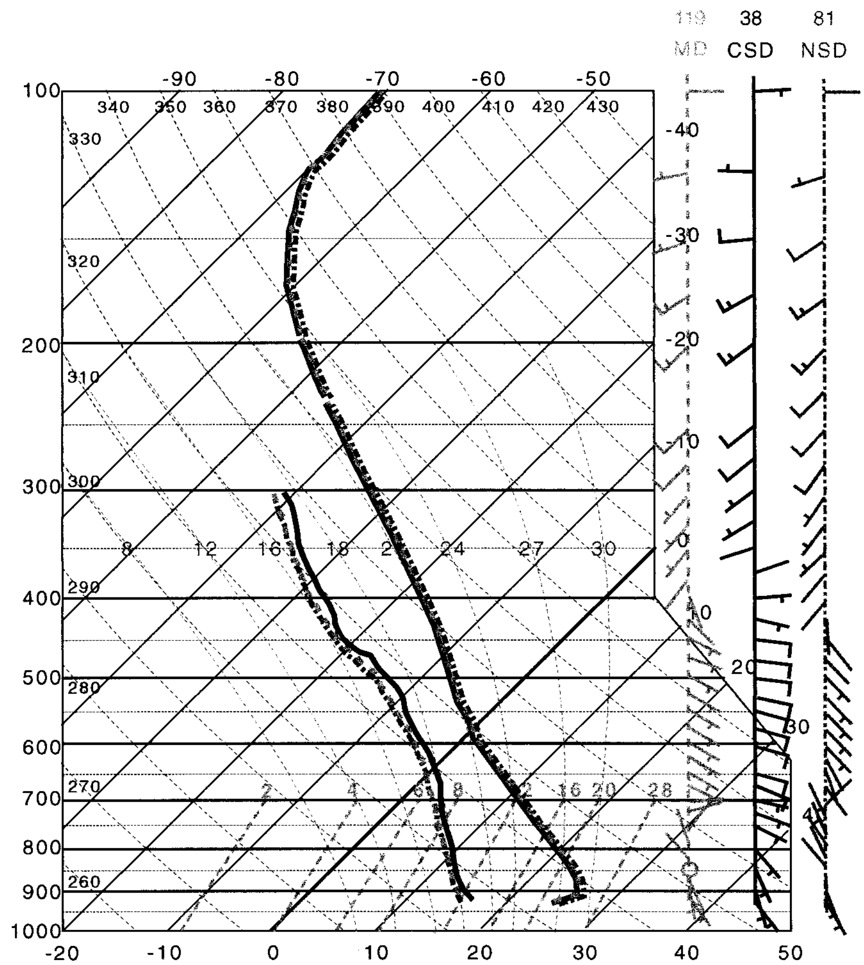

FIG. 9. Average TUS 1200 UTC skew *T*–log*p* sounding plot for 119 monsoon days (dashed), 38 CSDs (solid), and 81 NSDs (dash–dot). Winds are 5 m s^{-1} for full barbs and 2.5 m s^{-1} for half barbs.

surges of moisture northward from the Gulf of California appear to affect the convective environment across much of Arizona and the lower Colorado River basin. These studies are of a case study nature and little has been done to examine whether surges routinely cause immediate increases in thunderstorms. Forecasters in Phoenix have noted anecdotally that a strong moisture surge across Phoenix appears to reduce the likelihood of thunderstorms in the short term. This seeming paradox results because the surges of air from the northern Gulf of California typically bring large increases in dewpoint and significant cooling in the lowest levels (e.g., Douglas 1995). Thus, even though a surge may immediately increase the potential instability, it also produces a boundary layer structure that requires deep lifting to release the instability.

The surface data for CSDs were examined to determine if surges appeared to have a direct influence on the events studied. The criteria used to indicate a surge at Phoenix were quite simple: an increase in dewpoint temperature of 4°F or more during a 2 h or shorter period that maintained itself; the dewpoint increase had to occur with winds from, or a shift to, directions from south-southwest to west. The data on CSDs were scanned from local midnight until the time that thunderstorms began in the Valley, and the data were scanned for the entire day prior to the CSD. Moisture surges occurred on only 3 of the 58 CSDs and these surges occurred during the afternoon or evening. There was only one surge noted on the day immediately prior to any CSD. Thus, the surface data appear to indicate that surges usually are not immediately associated with outbreaks of storms in the Valley. Their role in determining the larger time- and space scale environment that leads to CSDs remains to be determined.

4. Discussion

The daily evolution of surface conditions at Phoenix and the characteristics of the 1200 UTC sounding at

Tucson have been examined to illustrate important meteorological attributes of the summer monsoon as they relate to thunderstorm occurrence in central Arizona. The focus has been on identifying undisturbed precursor conditions that lead to afternoon and evening thunderstorms in the Phoenix area. The local observations indicate few reliable signals that forecast the occurrence of thunderstorms in the Valley on monsoon days. However, the decreased diurnal amplitude of surface moisture changes suggests that increased/deeper lower-tropospheric moisture exists over the Phoenix area on days during which storms occur in the Valley. This signal likely cannot be detected by the forecaster, except in the most pronounced cases, without examining the local vertical moisture profile. Since the Valley has no representative operational upper-air sounding site, this is generally not possible. The 1200 UTC Tucson sounding, the nearest upper-air sounding site, cannot be considered representative of the low-level conditions over the Valley, since no significant thermodynamic differences are found between monsoon days on which storms do and do not occur in the Valley.

The 1200 UTC Tucson sounding does contain information in the vertical wind profile that may help the Phoenix forecaster infer the evolution of the lower-atmospheric moisture content and the potential for convection over the Valley. During a majority of no-storm days in the Valley, light northwesterly winds are evident above the nocturnal boundary layer up to approximately 700 mb. Advection of drier, Pacific air from the north and west apparently occurs on these days, reducing the total low-level mixing ratio, and stabilizing the atmosphere over the Valley. Midlevel (i.e., 700–375 mb) easterly winds are more favorable for steering storms off the higher elevations and over the low deserts on days when afternoon storms occur over the Valley.

An operational upper-air sounding at Phoenix during the summer monsoon period would provide the forecaster much needed local information, that is, information on the low-level moisture content and evolution of the convective potential. Research soundings in the Phoenix area during the past several summers have provided considerable forecasting utility (see Dempsey et al. 1998), and the Salt River Project is currently working in collaboration with the NWS to take a routine morning sounding at the forecast office. The low frequency of precipitation and convective events around 0000 UTC in the Valley suggests that a Phoenix sounding would be more representative of the conditions over the Sonoran Desert than the Tucson sounding.

The NWS and University of Arizona researchers are exploring the use of high-resolution mesoscale prediction models to improve summer forecasts of thunderstorms (see Farfán et al. 1998). Initial evaluation of these forecasts, both in real time and retrospectively, indicates that the National Center for Atmospheric Research–Pennsylvania State University Mesoscale Model version 5 (Grell et al. 1994) mesoscale prediction model is unable to forecast accurately the thermodynamic structure of the afternoon boundary layer over Arizona. The reasons are not clear, but it is expected that more accurate low-level thermodynamic data [such as might be supplied by additional soundings or by improved satellite soundings—see Holt et al. (1998)] would help to improve the model's performance. It is clear that without improvements in the model physics and initialization data, this approach will do little to improve area-specific forecasts for small regions such as the Valley. Forecasters and researchers will undoubtedly need to draw upon various innovative technologies (e.g., satellite-borne sounders, mesoscale model simulations, research upper-air soundings, and radar observations) in order to describe and predict the evolution of the boundary layer that leads to convective storms in central Arizona.

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