Large-Scale Patterns Associated with Severe Summertime Thunderstorms over Central Arizona

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ABSTRACT

Severe thunderstorms are relatively rare over Arizona and occur most frequently during the summer monsoon period, that is, July, August, and early September. Forecasting in Arizona during the summertime is quite difficult and skill scores are low for both precipitation and severe thunderstorm watches and warnings. In the past, due to the sparse population of Arizona, severe thunderstorms usually impacted few people and were considered relatively insignificant events. However, over the last 20 years, the population of central Arizona has grown dramatically, and the impact of severe thunderstorm and flash flood occurrences has also increased.

Synoptic conditions associated with 27 severe thunderstorm events that occurred in central Arizona during the summer monsoon have been examined systematically and compared to long-term mean July conditions. The period of study covered 1978 to 1990, and cases selected were limited to the high population area of central Arizona. McCollum subjectively identified three distinct large-scale patterns (types I, II, and III) that were associated with the severe thunderstorm events. Significant large-scale departures from mean conditions are used to characterize the Arizona severe weather environment for these three pattern types. Significant pattern anomalies tend to be far removed from the state, typically by 1000 to 2000 km. Thus, even though the summertime environment may seem locally stagnant, a large-scale perspective is required to monitor the day to day evolution of the severe weather environment in the Southwest.

The key factor affecting convective instability at lower elevations, that is, in the deserts of central Arizona, is the amount of low-level moisture present. Severe storm conditions are distinctly more moist and unstable than average from the surface to 700 mb. The standard level charts for the severe weather patterns indicate that the Gulf of California plays an important role in providing a source for this moisture.

The summertime severe thunderstorm environment over the southwest United States is distinctly different than central and eastern United States storm settings, which are well known based upon years of study of substantial numbers of events. In general, the environment in which central Arizona severe monsoon thunderstorms occur is one of weak synoptic-scale flow, significant lower- to midtropospheric moisture, and moderate instability. The nature of subsynoptic circulations that initiate and support severe weather over central Arizona is difficult to infer. However, the existence of repetitive, large-scale patterns suggests that forecasting for the general threat of severe summertime thunderstorms can be improved.

1. Introduction

Although severe thunderstorms are relatively rare over Arizona, they occur most frequently during the summer monsoon period, that is, July, August, and early September (Schmidli 1986). Downbursts, dust and sand storms, heavy rain, hail, small tornadoes, and intense cloud to ground lightning are observed practically every active monsoon season (Idso et al. 1972; Idso 1975; Hales 1975; Randerson 1986; Schmidli 1986; Brazel and Nickling 1986; Smith and Gall 1989; McCollum et al. 1995). Given the weak synoptic-scale flow over Arizona during the summertime (Douglas et al. 1993), severe storm analysis and forecasting techniques developed primarily for thunderstorm events over the Midwest (e.g., Miller 1972) usually provide little insight into predicting monsoon severe thunderstorm activity. For severe thunderstorm warnings issued by the National Weather Service forecast office in Phoenix during recent years, the critical success index has been less than 0.2, and the false alarm rate greater than 0.6 (verification statistics provided by the National Severe Storms Forecast Center (NSSFC), Kansas City, Missouri).

These low skill scores [see Doswell et al. (1990) for a discussion of skill measures for rare event forecasts] highlight the difficulty of the forecast task in Arizona during the summertime. Similar difficulties are experienced at the NSSFC, where from 1986 to 1989 during July and August only one severe thunderstorm watch was issued for central Arizona (watch data provided
days. Operational numerical weather prediction models, not surprisingly, also perform poorly during the summer over Arizona. Junker et al. (1992) showed that for heavier precipitation events (accumulations of greater than 0.25 in.), the nested grid model (NGM) and medium-range forecast model (MRF) exhibited the lowest forecast skill over the southwest United States. Miranda and Reyes (1992) showed that in 1990 the mean 1000-mb winds in the initial NGM analyses were approximately 180° out of phase with the winds observed over the Gulf of California and northwest Mexico. Dunn and Horel (1994a,b) have also studied 1990 cases for Arizona and shown that National Centers for Environmental Prediction (NCEP) models (NGM and eta) were not able to predict the development of significant convective precipitation events.

In the past, due to the sparse population of Arizona, severe thunderstorms usually impacted few people and were considered relatively insignificant events. However, over the last 20 years, the population of central Arizona, specifically the Phoenix metropolitan area, has grown rapidly. For example, the population of Phoenix has increased by 46% and its many suburbs have grown by 50% to 300%. Coincidentally, the impact (and cost) of severe thunderstorm and flash flood occurrences within the Phoenix metropolitan area has also increased, and a growing need exists to document conditions that lead to severe thunderstorms over the deserts of central Arizona. This paper presents results from a study of a limited number of severe thunderstorm events that occurred during recent years and provides an initial documentation of large-scale meteorological patterns that support severe weather events in central Arizona.

2. Background
a. Regional geography

The topography of southwest North America is varied and complex (Fig. 1a). In northwest Mexico, the Sierra Madre Occidental is oriented northwest–southeast and forms the southern extension of the North American Continental Divide. Ranging from 2000 to 3000 m in height, the Sierra Madre Occidental is a significant mountain range between eastern and western Mexico. In the United States, the Rocky Mountains extend along a north–south line through central New Mexico and west-central Colorado. Between the Sierra Madre Occidental and the Rocky Mountains, average terrain heights are approximately 1500 m (i.e., about the 850-mb level). Mountains, ranging from 1000 m to just below 2000 m in height, form the spine of Baja California. These mountains effectively separate cool marine surface air over the eastern Pacific from hot, humid air that characterizes the Gulf of California summertime boundary layer (Badan-Dangon et al. 1991).

1 STORM DATA is published monthly by the National Climatic Data Center, Asheville, NC 28801. This publication summarizes significant weather events for each of the 50 states.
The topography of Arizona is also dramatic. Much of the northeastern half of Arizona (Fig. 1b) is higher than 1500 m in elevation. This region includes the White Mountains in east-central Arizona, the Colorado Plateau in the northeast, the Kaibab Plateau in northern Arizona, and the Mogollon Rim, which extends from northwest to southeast, in north-central Arizona. The southwestern half of Arizona is mostly low desert lying below 600 m. In general, the topography of Arizona slopes downward from northeast to southwest. The general topographic gradient is strongest in central Arizona where higher terrain lies in a semicircle around the northeastern flank of the lower desert.

b. Climatological background

During an average year, northwest Mexico and the southwest United States fall under the influence of markedly different mid- and upper-tropospheric flow regimes. From late autumn until early summer, westerly flow and associated disturbances account for most of the precipitation over this region (Schmidt 1986). During early summer, the westerlies shift poleward and the subtropical ridge expands northward and westward over North America. This shift in the mid- and upper-tropospheric pattern results in the establishment of anticyclonic mean flow through most of the middle to upper troposphere over northwest Mexico, New Mexico, and Arizona (Bryson and Lowry 1955; Douglas et al. 1993) by early July. During this same period, surface low pressure develops over the Great Basin in response to intense solar heating.

The reversal of flow in the middle and upper troposphere is normally followed by an increase in tropospheric moisture, convection, and precipitation across northwest Mexico and the southwest United States (Bryson and Lowry 1955; Sellers and Hill 1974). The seasonal increase in moisture and precipitation has been referred to as the Arizona and/or the southwest area monsoon by many researchers (Bryson and Lowry 1955; Brenner 1974; Tenharkle 1980; Schmidtli 1986; Moore et al. 1989; Adang and Gall 1989) because of some similarities to the southwest Asian monsoon. Douglas et al. (1993) referred to the phenomena as the “Mexican Monsoon” because the most dramatic effects occur over northwestern Mexico. The phenomenon will be referred to simply as the “monsoon” in this paper.

During the monsoon, Carleton (1985, 1986) observed that rapid increases (monsoon bursts) and decreases (monsoon breaks) in cloud cover (satellite observed cloud of all types) over the southwestern United States (Colorado, Utah, most of California, Arizona, New Mexico, and northwestern Mexico) were common. The monsoon bursts (breaks) occur on timescales of days (weeks) and appear to be modulated by synoptic patterns that help organize convectively favorable (unfavorable) environments. In particular, during Carleton’s burst events (i.e., periods of enhanced cloudiness over this large regional domain) the higher terrain areas of Arizona, that is, the White Mountains, the Mogollon Rim, and the Kaibab Plateau, experience increased rainfall. Carleton developed a number of mean synoptic patterns associated with these breaks and bursts; however, his work has little direct relevance to severe thunderstorms over central Arizona. Indeed, only two of the burst events documented by Carleton over three summers also had severe thunderstorms reported in Maricopa or Pinal counties in central Arizona.

Watson et al. (1994a) also composited upper-air data relative to breaks and bursts in monsoon thunderstorm activity. They used lightning strike data gathered over Arizona during a 6-yr period to determine break and burst periods, which typically covered several days. Again, their composites have little direct relevance to severe thunderstorm events over central Arizona since they did not correlate the lightning activity with severe weather occurrences. Indeed, the complexity of analyzing and understanding the subtle large-scale meteorological patterns of the monsoon period is well illustrated by the fact that Watson et al.’s (1994a) overall composite 500-mb chart for Arizona bursts is very similar to Carleton’s (1986) composite pattern for breaks (compare Carleton’s Fig. 5b with Watson et al.’s Fig. 18c). Remember that Carleton considered cloud coverage over a large region of the Southwest United States to define bursts, whereas Watson et al. looked at lightning counts only over Arizona to make their definitions.

On shorter timescales of a day, there is an early afternoon peak in thunderstorm activity in the higher terrain of Arizona and northwest Mexico. The majority of these storms are characterized by local heavy rain, occasional lightning, and moderate gusty winds but rarely exceed severe levels (Balling and Brazel 1987; Maddox et al. 1991). During the late afternoon and evening, the highest frequency of thunderstorm activity tends to shift to the lower deserts of central Arizona and northwest Mexico (Hales 1977; Balling and Brazel 1987; Maddox et al. 1991; Watson et al. 1994b). These thunderstorms often produce locally severe weather. The data of Watson et al. (1994b) clearly show a shift in cloud to ground lightning activity from higher terrain into the low desert during the early to middle nighttime hours. Their data also show dramatically reduced total hourly counts of lightning strikes as storms redevelop into the low deserts (see their Fig. 13). Since storms after dark in the low desert, at least from the authors’ personal experience, frequently produce spectacular displays of cloud to ground lightning, Watson et al.’s data suggest that only on limited days does the downslope propagation process actually lead to low desert storms, even though moisture values are typically higher toward the lower elevations.
c. Thunderstorm moisture sources

Early investigators believed that the primary moisture source that lead to thunderstorms during the monsoon was the Gulf of Mexico (Jurwitz 1953; Bryson and Lowry 1955; Green and Sellers 1964). They hypothesized that moisture from the Gulf of Mexico was advected into southwestern North America via mid- and upper-tropospheric easterly flow (Bryson and Lowry 1955). However, Hales (1972, 1974) hypothesized that the Gulf of California could act as a channel for surges of moisture from the tropical Eastern Pacific. Badan-Dangon et al. (1991) and Douglas et al. (1993) showed that in the lowest 50–100-mb layer above the surface, southerly flow was the most frequently observed wind over the northern Gulf of California during the monsoon. The mean, low-level southerly flow suggests that boundary-layer moisture should be advected systematically northward from over the Gulf of California. Brenner (1974) and Hales (1974) suggested that northward surges of low-level moisture may be modulated by the strength of both the surface heat low over the southwest United States and the surface high pressure at the southern end of the Gulf of California. McCollum et al. (1995) have shown that the Gulf of California can provide low-level moisture that dramatically increases the convective instability of the air mass over central Arizona substantially.

Rasmussen's (1967) study of water vapor transports over North America found distinctly different summertime moisture flux patterns to the west and east of the Mexican Plateau, that is, zonal vapor flux calculations for July indicated the Caribbean Sea to be the dominant source region with weak easterly flux over most of Mexico and a change of sign to zonal drying observed over Sonora and Baja. For meridional fluxes, his charts showed a source region and southerly flux centered over the western Gulf of Mexico that was distinct and separate from a meridional source region centered on the Gulf of California.

Mountain barriers in central Mexico and New Mexico clearly block direct zonal transports of low-level moisture from the Gulf of Mexico into the Southwest. Regardless of original source, it is apparent that mid- and high-level moisture over the Southwest has been transported from low levels in the vertical, most typically by convection over central and western Mexico (Douglas et al. 1993). The midlevel moisture, which is advected around the anticyclone by the horizontal flow, can provide a source of instability for mountain thunderstorms over Arizona, which recycle some of the moisture into lower levels through rainfall and evaporation.

d. Past severe thunderstorm studies

Historically, limited observational data in Arizona has made it difficult to investigate the character of the environments conducive to severe thunderstorms and associated phenomena in detail. Hales (1975) used low-resolution satellite imagery and crude air traffic control radar information to document the long life of an organized, severe mesoscale convective system that occurred in August 1973. This system apparently formed ahead of an inverted trough at 300 mb that was moving northwesward in the subtropical easterlies.

Randerson (1986) used satellite and surface data to document the life of an unusually large and long-lived severe mesoscale convective system that occurred in August of 1981. This system brought severe weather to Utah, Arizona, California, and particularly southern Nevada. It appears to have formed ahead of an unusually strong midtropospheric, cut-off low and associated short-wave trough in the westerlies. This convective system then propagated south-southwestward into the subtropical, monsoon flow regime over the lower Colorado River basin. This system occurred in an environment with upper-tropospheric westerlies positioned above the hot, unstable boundary-layer conditions associated with the monsoon regime. McCollum et al. (1995) studied a somewhat similar event that affected central Arizona during July of 1990.

Smith and Gall (1989) showed that the developments of three different, tropical-like severe squall lines over southern Arizona and northern Mexico were each associated with a strong ridge over the western one-third of the United States and a deep trough over the eastern United States. Each of these long-lived and organized severe weather episodes appears to have been associated with an inverted, middle to upper-level trough moving to the west in the subtropical easterlies. Brazel and Nickling (1986) identified a qualitatively similar pattern associated with Arizona dust storms generated by summer thunderstorms. Maddox et al. (1980) showed that significant flash floods were also associated with this type synoptic pattern.

Most of these past studies are essentially case examinations of specific events, and the lack of any systematic documentation of synoptic and thermodynamic settings in which Arizona severe monsoon thunderstorms occur leaves operational forecasters with few documented sources to draw on to improve forecast techniques. In this paper, the large-scale conditions associated with severe monsoon thunderstorms for almost 30 different events over central Arizona are investigated using routinely available, operational synoptic observations. While the size of the database/event set is small from a statistical analysis perspective, a number of recurrent features have been identified subjectively.

e. Identifying severe thunderstorm events

For the purpose of this study, severe thunderstorm events were identified using the following criteria: winds greater than 50 kts, wind damage, and rainfall of more than an inch in less than three hours with flash flooding.
Severe weather with the cases chosen occurred in the greater Phoenix metropolitan area and nearby towns (see Fig. 1b). The focus was on this region, since we could obtain reasonably reliable reports of severe weather from this high population density portion of the state. Since severe thunderstorms are relatively rare, and since most of Arizona remains uninhabited or very sparsely populated, it is not possible to develop reliable severe thunderstorm statistics for the state. Many events are not reported. The rapid population growth in recent years also means that the character and extent of storm reporting is changing rapidly in the Phoenix and Tucson metropolitan areas, that is, more storm reports as these cities expand in areal coverage. Because of this, there is no reliable, long-term database that can be used to stratify synoptic meteorological data for storm versus nonstorm days. Regardless, we were able to identify 31 central Arizona severe thunderstorm events for analysis (see Table 1, section 4). From the perspective of central United States studies, this is a very small sample, but it is the largest set of severe thunderstorm events examined for the Southwest to date and provides an initial documentation of important thunderstorm patterns.

All of the cases occurred between 1978 and 1990 during July or August. The Southwest Area Monsoon Project (SWAMP) Operations Summary (Meitin et al. 1991) and STORM DATA were used to identify the events. Since the field project probably led to the most documented period of storm activity in the Phoenix area, and since 1990 was a very active thunderstorm year in Arizona, our database is biased toward 1990. The date, time, and observed weather accompanying each severe thunderstorm case are listed in Table 1. Note that a small tornado occurred during one of the events. Hail rarely occurs over the low deserts, and when it does, it is usually small. Hail with at least one-half inch diameter occurred during three of the events.

f. Data analysis

Upper-air soundings were obtained for the 31 storm events and mean 1200 and 0000 UTC soundings (data were averaged at 25-mb increments) were generated for Tucson (Fig. 1b). Various thermodynamic parameters were computed using a lifted parcel with the mean temperature and mixing ratio of the first 100-mb layer above the surface. Computations were done on the mean sounding data, and there were no significant differences between the mean value of parameters computed for each individual sounding versus parameters computed from the mean sounding. For each severe thunderstorm case, a set of upper-air charts (1200 and 0000 UTC 850–250 mb) and surface maps (1200 and 0000 UTC) were analyzed. Average 1200 UTC charts were prepared for the 850-, 500-, and 250-mb levels. We chose these levels to include conditions in the boundary layer and the middle and upper troposphere.

We have not considered the 700-mb level, because as is shown later in long-term mean Tucson soundings, it is typically within the afternoon boundary layer over most of Arizona in summer.

Although Tucson is 160-km south-southeast of Phoenix, this site is the most representative one available to examine conditions associated with storms in the Phoenix area and provides the data that must be used routinely in operational forecasting. McCollum et al. (1995) have shown a case for which the Tucson data were not representative of conditions in the Phoenix area, and it is not clear at this time how often there are substantial differences across this relatively short distance. The Phoenix region is one of the largest metropolitan areas in the United States that has a substantial thunderstorm forecasting challenge but no local operational upper-air sounding site, making study of central Arizona storms most difficult.

3. The climatological summertime setting

For comparative purposes, mean July 1200 UTC climatological charts for 850-, 500-, and 250-mb and Tucson 1200 and 0000 UTC mean soundings were generated using 30 years (1958–1988) of upper-air data. We emphasize the 1200 UTC data, because these are the observations the operational forecaster must use in developing the afternoon and nighttime forecast. Through July and August, no significant changes occur in the mean large-scale pattern over southwest North America (e.g., see Korte 1971), and the July means were used as representative of the summertime monsoon period. Given the unreliable character of the long-term documentation of thunderstorm and severe weather events over central Arizona, long-term means cannot be generated for nouthunderstorm or nonsevere thunderstorm conditions. However, the mean climatological charts typically available to forecasters contain some signal from all observed weather events and are similar to the long-term, average data used here.

The long-term mean charts are shown in Fig. 2. The analyses generally show contour intervals that are used on operational charts; however, in some cases the standard operational contour intervals reveal so little about the summertime patterns that the intervals have been enhanced. At 850 mb (Fig. 2a), there is a dominant region of lower heights centered over the Great Basin and height gradients are very weak over all of the West. The hottest air at 850 mb is centered to the south of the cyclonic wind circulation, reflecting the higher elevations of the upper-air stations in the northern Great Basin. There are two distinct axes of high moisture content. One is over the southern Plains, reflecting the persistent low-level southerly jet blowing northward from the Gulf of Mexico. The other is over western Mexico and Arizona, reflecting the persistent but light winds from the south off the Gulf of California.

At 500 mb (Fig. 2b), the subtropical ridge extends from southern California eastward to central Florida,
with a broad anticyclonic circulation centered over eastern New Mexico. Height gradients are weak, and the anticyclone is centered north of the region of warmest air. The most distinct feature of the mean 500-mb chart is the distribution of dewpoint temperatures; the axis of highest dewpoint temperatures lies essentially orthogonal to the winds and height contours from northwestern Mexico to the central Rockies. Conditions tend to be drier to the east of the anticyclone center and more moist to the west. Conditions also appear to be slightly cooler within the moist axis, probably reflecting cloudiness and evaporative cooling. It is important to note that the moisture axis is essentially oriented parallel to the higher terrain in Mexico and the Southwest United States, with the moisture ridgeline occurring to the west of the Continental Divide. This orientation leads to a distinct pattern of positive moisture advection from southwest to northwest to northeast of the high center and distinct negative advection (drying) from the southeast to south of the anticyclonic circulation. This indicates that the moisture advection patterns in midlevels result primarily from vertical moisture transport from lower levels by convective storms to the west of the Continental Divide and then, secondarily, by clockwise advection of the moisture around the anticyclone (also see Rasmusson 1967; Douglas et al. 1993).

A broad anticyclonic flow and ridge characterize the mean 250-mb chart (Fig. 2c). The ridgeline extends from northern Baja eastward to northern Florida. The anticyclone center lies over northern Mexico, well to the south and west of the high center at 500 mb. The
substantial vertical tilt of the mean anticyclone centers from 850 to 250 mb indicates that atmospheric structure during the monsoon period is far from that of an idealized, barotropic lower heat low–upper anticyclone.

These mean charts clearly show that there are no streamlines with a direct fetch from over the Gulf of Mexico to over Arizona. These charts support the findings of Rasmussen (1967), Hales (1972, 1974), and Douglas et al. (1993), indicating that low–midlevel moisture is not being advected directly by the monthly mean flow from the Gulf of Mexico area into the southwestern United States. When such transports occur, they are associated with transient eddies.

4. Severe thunderstorm patterns

An overview of the analysis charts for the individual severe thunderstorm cases indicated that conditions were somewhat similar for all events over the immediate Arizona area. This is due to the very weak height and temperature gradients present over the Southwest during the summer. McCollum (1993) subjectively “typed” the associated synoptic patterns considering the large-scale setting over most of North America using the 500-mb charts for each event. He identified three similar patterns recurring among the individual case events, and his results are used here. His subjective pattern decisions were based on height and flow patterns and the position of ridges and troughs relative to Arizona. This type of pattern analysis has been used in other studies of relatively rare weather events (e.g., Maddox et al. 1979, 1980; Doswell 1980; Johns 1982).

Because of the “first look” character of this study and the very small number of documented severe storm reports in central Arizona, we chose not to attempt more quantitative statistical approaches for pattern typing [e.g., use of eigenvector analysis to determine recurring patterns in a large dataset as per Kutzbach (1967), Brinkman (1981), and Schaefer and Doswell (1984)]. However, subjective synoptic pattern typing has proven to be a very robust approach for use in weather analysis and forecasting [e.g., weather patterns developed by Elliot (1941) and Miller (1959) remain valid and in use today].

There are three distinct, recurring patterns at 500 mb for the limited set of 31 cases. The patterns identified (simply called type I, II, and III) are illustrated by the typical 500-mb streamlines shown for each type in Fig. 3. Table 1 also indicates the pattern type associated with each severe thunderstorm case. Four of the 31 severe thunderstorm cases did not correspond closely with any of the three pattern types identified; they are marked with an “a.” Three of these cases were associated with the remnants of decaying tropical storms and were not considered further. The other case (21 July 1984) involved an anomalously deep trough off the southwest coast of the United States. This pattern appeared only once in the sample and was not considered. The remaining 27 cases were evenly divided between the three pattern types.

We have analyzed the departures of each pattern type from long-term climatological conditions. Note that because of the large number of cases from 1990, our sample probably does not reflect a typical annual distribution of the types (i.e., there was an unusual
Table I. The date, time (local standard time), weather phenomena, damage occurrences of greater than $500,000, and associated synoptic classification of cases.

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<td>2300</td>
<td>W</td>
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* Did not fit into any of the pattern types. ND = next day; W = winds greater than 50 k; F = flash flood; H = hail greater than 0.5-in. diameter; X = damage greater than $500,000.

The predominance of west to northwesterly flow regimes during the 1990 monsoon period, and five of the type III patterns occurred in 1990).

a. Type I setting

The type I severe thunderstorm setting results from a northward and westward shift in the subtropical ridge position. At 850-mb (Figs. 4a,b), this pattern is characterized by higher heights over most of the analysis domain. Temperatures are slightly cooler over the southern quarter of the analysis area, reflecting the northward shift in the position of the subtropical ridge. A region of warmer temperatures over the northern United States east of the Rockies is also distinctly drier than climatological conditions. The most prominent characteristic of the 850-mb level is the large anomaly in dewpoint temperatures of more than +4°C over much of the Southwest.

Conditions at 500 mb (Figs. 4c,d) are dominated by anomalously high heights and warm temperatures from the Pacific northwest eastward to the Great Lakes, again reflecting the distinct northward shift of the subtropical ridge. The 500-mb anticyclone center has shifted eastward to northern Oklahoma, although there is indication of a secondary anticyclone center near the four-corners region. The moisture axis has shifted westward in response to the broad changes in the height and wind fields, and a substantial positive dewpoint anomaly extends from the Gulf of California northward across the Great Basin. Anomalies at 250 mb (Fig. 4e) are similar to those at 500 mb, with substantial height increases extending from the Pacific Northwest to the Great Lakes. (Note that the type I height perturbations are greatest and most distinct at 250 mb, whereas the moisture perturbations are most pronounced at 850 and 500 mb.) The 250-mb anticyclone center lies over the Arizona–New Mexico border region. Steering level winds for thunderstorms (i.e., 500 mb) over central Arizona tend to be from the east to southeast, while upper-level winds (i.e., 250 mb) tend to be from the south to southwest.

b. Type II setting

The type II severe thunderstorm pattern is much different from both the type I setting and the long-term climatological summertime setting. The type II 850-mb charts (Figs. 5a,b) are dominated by unusually high heights and a distinct high pressure center over the north-central United States. Unusually cool temperatures, while centered in the northern United States, extend all the way into southeastern Arizona. In contrast, the Pacific Northwest is quite warm. However, somewhat similar to the type I setting, unusually high 850-mb dewpoints extend from west Texas to northern Mexico to the Pacific Northwest. In the mean, it is clear that a strong cool front tends to lie across the southern Plains and that it likely extends into northern Mexico–southern Arizona.

The 500-mb height and temperature perturbation analyses (Figs. 5c,d) show a very pronounced high–low couplet over western Canada and the Great Lakes region. The three severe convective systems studied by Smith and Gall (1989) clearly occurred within a type II setting, as illustrated by their 500-mb analyses (their Fig. 11). The anticyclone center is shifted westward and northward to southern Utah. A band of high dewpoints curves from the southern Plains to the Northwest. The central and northern portions of the United States are significantly drier than normal. Features at 250 mb (Fig. 5e) are similar to the positive height anomaly, exceeding 200 m over western Canada! The 250-mb anticyclone is centered over extreme southwestern New Mexico. The shifting position of the anticyclone center with height leads to steering flow (i.e., winds at 500 mb) from the east to northeast for thunderstorms over central Arizona, but with anvil level winds blowing the high clouds off the thunderstorm tops to the northeast.
FIG. 4. Type I pattern anomalies at 1200 UTC. Winds shown are the pattern mean winds (full barb = 5 m s⁻¹). (a) Here, 850-mb heights (m) are dark contours and height anomalies are light contours; (b) 850-mb temperature anomalies (°C) are light contours and dewpoint anomalies (°C) are dashed contours; (c) and (d) the 500-mb anomalies shown as in (a) and (b) above; (e) the 250-mb chart with pattern mean heights shown in dark contours, height anomalies in light contours, and temperature anomalies in dashed contours.
FIG. 5. Type II pattern anomalies at 1200 UTC shown as in Fig. 4.
d. Type III setting

The type III pattern is essentially the opposite, or "antipattern," of the type I pattern. In this situation, the subtropical ridge is depressed substantially to the south of its typical summertime position. This is an unusual situation in that low-level flow remains essentially in a "monsoon" regime, while mid- and upper-level westerly flow rides over the hot, unstable low-level air. The 850-mb charts (Figs. 6a,b) are characterized principally by unusually cool conditions over the eastern two-thirds of the United States and warm anomalies over the northwest. Much of the northern two-thirds of the United States is unusually dry. The dominant feature at low-levels is the region of high dewpoints over the lower Colorado River basin, northwestern Mexico, and southern Arizona.

At 500 mb (Figs. 6c,d) heights are anomalously low over most of the United States, and only the far western regions of the United States and Canada have unusually high heights. The anticyclone in the west is shifted southwestward and is located somewhere west of Baja. There is a distinct break (i.e., presence of a weak trough) in the 500-mb subtropical ridge over Texas and northern Mexico. The temperature perturbations are similar to the height perturbations. But it is interesting that the 500-mb setting remains unusually moist throughout all of the Southwest. Since flow is westerly, the source of the moisture is probably vertical advection accomplished by persistent convection over the mountains of the far West and Southwest. At 250 mb (Fig. 6e), heights are unusually low over all of the eastern two-thirds of the continent, while heights are high over the west and northwest and probably over the Gulf of Alaska. The anticyclone center is suppressed south and centered over Sonora, Mexico. Once again, however, upper-level winds are considerably different than the midlevel, convective steering flows.

e. Mean soundings at Tucson

Long-term mean morning and afternoon soundings for Tucson (Fig. 7) show strong diurnal heating in low-levels below 600 mb, and the afternoon boundary layer, as indicated by the depth of the nearly constant potential temperature layer, extends above 700 mb. However, the afternoon sounding is a degree or two warmer at all levels (this surprising aspect of the data is discussed at the end of this section). Moisture changes little during the day except for a substantial decrease in lowest levels, that is, below 800 mb. The dewpoint temperature at the surface (850 mb) decreases by 3.8°C (1.0°F) from 1200 to 0000 UTC. Since dewpoints remain essentially unchanged in the upper portion of the afternoon boundary layer (i.e., a decrease of only 0.1°C at 750 mb), the diurnal cycle appears to advect drier low-level air into the Tucson area during the day. Indeed, the mean winds show a dramatic diurnal cycle in lowest layers. Afternoon winds are from the northwest, off the lower desert regions, and these typically bring in drier, more stable conditions. There is essentially no convective instability at Tucson in the long-term mean afternoon sounding.

The long-term mean Tucson soundings are shown in Fig. 7, with the average soundings for the three severe thunderstorm patterns overlain. At 1200 UTC (Fig. 7a) the severe storm environment is slightly warmer (warmer) in the lower (upper) troposphere. The principal difference is that the substantially higher dewpoints present in the severe weather settings, as was also apparent on the anomaly charts shown earlier. By late afternoon (Fig. 7b), the severe storm soundings remain warmer than the low-level mean in the upper half of the troposphere. The primary difference is that in the severe storm setting high moisture contents persist and even increase slightly during the day, so that from the surface to 700 mb the severe storm setting is much more moist than the average environment. It is interesting that severe thunderstorms were reported in the Tucson area on only 8 of the 27 case days. This indicates that a separate examination of severe storm situations is needed for southeast Arizona.

The mean type I morning and afternoon soundings are presented in Fig. 8a. The most important feature of the mean soundings is that the moist and much more unstable conditions (note that the Lifted Index at 0000 UTC reaches −4°C). The afternoon, up-valley winds are not as pronounced as for the long-term 0000 UTC conditions, possibly leading to reduced advection of dry air in low-levels. The afternoon boundary layer is nearly dry adiabatic to 670 mb, presenting a very favorable environment for downbursts and strong outflows. For the type II mean soundings (Fig. 8b), low levels are drier than for the type I setting, and the diurnal cycle for the low-level winds is strongly damped in the afternoon. This may reflect the occasional presence of a surface cold front in southeast Arizona during this pattern, with large-scale pressure gradients opposing the afternoon up-valley flow regime. During the day the moisture increases substantially through a deep layer, again apparently due to advection processes. The soundings for the type III setting (Fig. 8c) are generally similar, although warming and drying occurs during the day in a deep layer above about 650 mb—apparently this reflects the large-scale setting, where dry northerly to westerly flow prevails, that is, the atypical summertime pattern when the subtropical ridge is displaced far south of its usual position.

All of the severe thunderstorm average soundings exhibit much enhanced low-level moisture. (Note that mean mixing ratios for the lowest 100 mb are 12–14 g kg⁻¹ for the severe storm setting, whereas the long-term mean afternoon mixing ratio is only about 8.5 g kg⁻¹.) The severe storm mean soundings are quite unstable and highly conducive to development of strong winds at the surface. It should be pointed out that this downburst environment is far different than
FIG. 6. Type III pattern anomalies at 1200 UTC shown as in Fig. 4.
that typically associated with western United States dry downbursts, say in the Denver area, where there is only slight instability at middle levels (Brown et al. 1982). Central Arizona downbursts appear to be more similar to moist microbursts in the southern Plains or in the Southeast (see Eilts and Doviak 1987 or Wakimoto and Bringi 1988) where there can be both substantial convective instability and a deep, subcloud adiabatic layer.

All of the mean soundings indicate that essentially the entire atmosphere warms 1°–2°C or more between morning and evening! This is not a physical reality above about 600 mb, and the cause is related to the timing of the flights. Morning flights in this time zone occur essentially during darkness, while the 0000 UTC flights occur during a fairly high sun angle time of day—release at about 1600 LST. This situation leads to radiation heating of the instrument package during the 0000 UTC flight and erroneous temperatures in the mid and upper atmosphere. Schmidlin (1991) and Luers and Eskridge (1995) have shown that afternoon upper-air sounding temperature errors are typically only one-half or one degree Celcius or less below 200 mb. There appears to be a considerably larger effect present in the Tucson data. Careful examination of this data problem is beyond the scope of this paper, but it should be noted that actual convective instability in Arizona during the late afternoon may be substantially greater than the operational sounding data indicate!

5. Discussion

We have begun to evaluate the utility of the severe weather patterns within a forecasting context; however, this process is not simple because of both the rare nature of severe weather occurrences and the lack of a long-term stable database of documented severe thunderstorm occurrences in central Arizona. We have examined July standard level charts for 1976 and 1977—the two summers immediately prior to the years used in the development dataset. The first two authors, RM and DM, using primarily the 1200 UTC 500-mb charts, independently “typed” each day (i.e., we carefully examined 62 days and then compared results). We disagreed on the “type” pattern present on only 11 days (i.e., our independent assessments agreed for 83% of the cases and our disagreements were easily resolved by a second look at the charts). The general flow patterns occurred as follows: no type—37; type I—17; type II—3; and type III—5 times. The most important aspect of these results is that the three pattern types do not merely represent the dominant 500-mb flow regimes that occur during the monsoon period. Approximately 60% of the days exhibited 500-mb height and flow regimes that did not fit any of the three synoptic, severe thunderstorm patterns.

We did not examine the other standard levels in detail nor did we attempt to examine the Tucson soundings for these two months. However, we did apply a second simple screening to the cases identified as severe thunderstorm patterns using the 850-mb 1200 UTC observation at Tucson. If the dewpoint at Tucson was not at least 11°C, the case was eliminated as a severe storm pattern. The threshold is the mean dewpoint at Tucson on severe thunderstorm event days, minus its standard deviation. We obtained the following results after applying this second test: no type—46; type I—11; type II—2; and type III—3. Thus, this
simple analysis led to our identifying 16 potential severe thunderstorm days in central Arizona. However, when we examined storm data for July 1976 and 1977, we found that severe thunderstorms in central Arizona were documented for only five days. Two of these were on pattern days and two were on pattern days that were eliminated in the 850-mb dewpoint screening process [probably indicating that the Tucson sounding was not representative of conditions in central Arizona—similar to the case documented by McCollum et al. (1995)]. The fifth case occurred with a deep trough along the West Coast that provided a more classic severe storm environment with strong wind shear but that was not a monsoon-type setting.

We have already discussed the weaknesses of the severe thunderstorm database for central Arizona; examination of the Phoenix surface observations leads us to believe that more severe thunderstorm events likely occurred during July 1976 and 1977 than were reported (e.g., thunderstorms occurred over the central
Arizona deserts on many more days than five). A rigorous evaluation and determination of essential information such as false alarm rates, etc., will have to await development of an adequate, extended database. Our preliminary evaluation does indicate that there is useful information in the synoptic data for helping the forecaster anticipate potential severe weather in Arizona.

The authors' personal experiences during the last two summer monsoon seasons continue to indicate that the severe thunderstorm patterns are robust and occur distinctly only during limited summertime periods. But two significant problems have been noted that limit the usefulness of these results for forecasters in Phoenix. First, pattern false alarms usually occur when there is a lack of boundary-layer convective instability in the low deserts (i.e., inadequate low-level moisture and/or heating). Second, since there are no upper-air soundings taken at Phoenix, the forecaster must seek out indirect cues as to whether or not significant instability is developing. The authors have found that this is can be a very difficult task (see McCollum et al. 1995) using routine operational observations. For example, the Gulf of California plays an important role in providing a source for low-level moisture and convective instability; however, there are few surface observations and no routine soundings to the southwest of Phoenix.

The standard level charts do indicate that patterns of vertical wind shear develop over central Arizona that favor (or at least are not hostile to) propagation of storms by new cell development from higher terrain into the low deserts. These wind patterns are characterized by considerable veering from steering levels (e.g., 500 mb) to anvil levels (e.g., 250 mb). Such a pattern moves the anvil and associated rainfall away from the region of new cell development "ahead" of the storms, which is important if rainfall is not to cool and stabilize the air within which new cell growth is needed if propagation toward the deserts is to occur.

During the monsoon period, synoptic conditions over the Southwest change only slightly. Subtle shifts in the weather pattern are very difficult to detect if the forecaster limits his/her attention only to the local or regional scale. The key large-scale anomalies, much like teleconnections, that define the Arizona severe weather environment (excluding the enhanced moisture signals present directly over the Southwest) tend to be far removed from the state, typically by 1000 to 2000 km. Thus, even though the summertime environment may seem locally stagnant, a large-scale perspective is required to determine how the severe weather environment in the Southwest is evolving day to day. The first systematic examination of severe thunderstorm settings in the Southwest, reported here, demonstrates the difficult nature of the forecasting problem.

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