J4.4 SUMMERTIME STORM INITIATION AND EVOLUTION IN CENTRAL ARIZONA

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1. INTRODUCTION

Traditionally, summertime precipitation in Arizona is characterized in terms of 'breaks' and 'bursts' in the North American Monsoon (NAM, e.g., Carleton 1986; Watson et al. 1994; Mullen et al. 1999). Breaks denote relatively dry conditions, whereas bursts denote relatively wet conditions. The diurnal climatology elucidates the tendency for storms to initiate first (near noon) over the Mogollon Rim and White Mountains, followed by initiation over the Southeast Highlands. During the afternoon, the storms move and redevelop southwestward down the central Arizona terrain gradient, and westward from the eastern terrain, culminating within the Sonoran Desert near sundown. This diurnal evolution is ubiquitous; it appears in diurnal storm climatologies using precipitation-gauge (Balling and Brazel 1987), lightning (Watson et al. 1984), or radar-mosaic (MacKeen and Zhang 2000) data.

Although this diurnal cycle is well known, individual days can depart markedly from this climatology. The goal of this study is to explore this variability in central Arizona precipitation by examining the role of terrain and associated synoptic conditions on preferred storm initiation locations and storm evolutions.

2. DATA

Two datasets are used to investigate the atmospheric processes related to storm initiation and evolution in central Arizona: Level II WSR-88D radar reflectivity data and 12 UTC upper-air data. The NAM seasons analyzed in this study include July 1997 and July 1999. Soon, the data will be expanded to include August. Analyses will span from July–August during each year because precipitation associated with the NAM usually begins in early July (Sellers and Hill 1974), and during September the NAM begins to dissipate. The analysis period begins in 1997 because it is the first year where radar data are available from both the Phoenix and Flagstaff WSR-88D sites. The 1998, 2000, and 2001 summer seasons are excluded due to large gaps in archived sounding data at Phoenix.

3. METHOD

Previous studies of storm occurrence in Arizona used precipitation or lightning data (e.g., Fujita 1962; Orville 1965; Balling and Brazel 1987; Watson et al. 1994b; King and Balling 1994) in place of single-radar data (Braham 1958; Ackerman 1959; Hales 1972b), owing to radar limitations such as beam blockage, decreasing resolution with increasing range, and anomalous propagation. In this study, such radar data limitations are addressed by adaptively mosaicing, or mapping, radar reflectivity data from multiple radars that observe storms in central Arizona (Zhang 2000).

The mosaic technique is performed on a Cartesian grid, which is 440 km x 440 km in the horizontal, and spans latitudinally from 32.04° N to 36.43° N, and longitudinally from 109.01° W to 113.04° W (Fig. 1). Grid resolution is 1 km in the horizontal, and 21 stretched levels in the vertical (surface to 12 km), such that height intervals increase hyperbolic-tangentially with increasing height. The result of the mosaic technique is a 3-D radar reflectivity mosaic that is produced every 10 min. While such a 3-D data set may be used to examine storm structure characteristics, the main interest in this study is whether or not weather echoes occurred within each grid box. Thus, to simplify processing, a 2-D mosaiced composite reflectivity product is used to discern weather from nonweather echoes. The composite reflectivity product is a grid of the maximum reflectivity value within each 1-km x 1-km x 12-km column.

Upper-air maps (1200 UTC) using Reanalysis Data and 12 UTC daily rawinsonde data collected at Phoenix, are used to investigate how synoptic-scale conditions relate to where storms tend to initiate and how they evolve. Whereas previous studies of storm development in and around Phoenix rely on rawinsonde data collected at Tucson (Maddox et al. 1995; Wallace et al. 1999), this study offers an examination of rawinsonde data collected at the new Phoenix rawinsonde site.

4. RADAR REFLECTIVITY REGIMES AND ASSOCIATED SYNOPTIC-SCALE CONDITIONS

Reflectivity regimes are determined subjectively by observing the diurnal evolution of reflectivity mosaics for each day in July 1997 and 1999, and five distinct regimes are found. In these five reflectivity regimes, composite reflectivity evolves over the following areas in central Arizona: 1) eastern mountains (7 of 58 days or 12% of events), 2) central and eastern mountains (14 of 58 days or 24% of events), 3) central mountains, eastern mountains, and Phoenix (15 of 61 days or 26% of events), 4) most of the domain (called widespread regime; 9 of 58 days or 28% of events), and 5) none (no radar echo forms; 10 of 58 days or 17%). Of the remaining 7 days, radar data were unavailable for 4 of them and 3 days did not fit into identified regimes.

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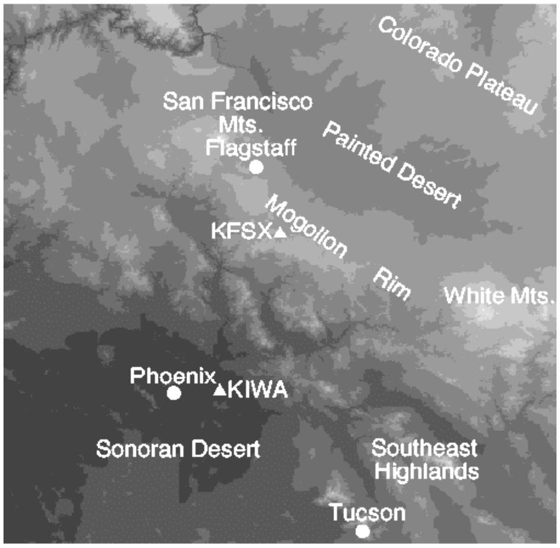

Figure 1. Domain of mosaiced radar data, including Phoenix (KIWA) and Flagstaff (KFSX) radar locations and major terrain features.

Characteristics of the evolution of each regime, such as areas where radar reflectivity tends to develop repeatedly, are analyzed by calculating the relative frequency of composite reflectivity values greater than or equal to 25 dB*Z* over the diurnal cycle of all days associated with each regime. The diurnal cycle for each regime is determined by using the following periods of reflectivity data for all days included in a given regime: 18–20 UTC (early afternoon), 22–00 UTC (late afternoon), and 02 UTC–04 UTC (evening). These relative frequencies are then displayed on a 1-km terrain grid from the United States Geological Survey (Fig. 1). A composite reflectivity threshold of 25 dB*Z* serves as a proxy for the convective storm development dominant in central Arizona during the summertime. Each reflectivity regime has a diurnal evolution that contains areas of repeated storm development over elevated terrain features. Such repeated storm development over elevated terrain illustrates the importance of terrain forcing in the initiation of moist convection in central Arizona during the summer season. Differences in the location of initial storm development among regimes suggest that differences in the interactions between terrain and synoptic-scale conditions, such as the direction of the flow approaching the mountains, may be regulating where storms develop.

Below, significant features of each regime are discussed in light of composited Reanalysis data and rawinsonde data.

a. Dry regime (DR)

The DR is characterized by days where storms fail to develop over central Arizona. During July 1997 the DR occurs more often than during July 1999 (i.e., 9 vs. 1 day(s), respectively). The more frequent occurrence of dry days in 1997 than in 1999 reflects the later onset of Arizona's summertime wet season during 1997 than during 1999 (i.e., 7 July vs. 2 July, respectively). Composite reanalyses of geopotential height (m^2s^{-2}) and specific humidity (kgm^{-3}) at 700 hPa and 500 hPa show that, in the mean, the wind profile is westerly with height over central Arizona and relatively moist air is located southward of Arizona. Such conditions result from zonal westerly winds northward of Arizona and a cell of high pressure southward of Arizona, whose horizontal ridge axis is located over northern Mexico and central Texas. This mean flow pattern typically results in the suppression of moisture, instability, and lifting mechanisms needed to support storm development.

b. Eastern mountain regime (EMR)

The EMR is characterized by storm development over the mountains of eastern Arizona and relative frequency maxima of reflectivity that occur over the White Mountains and the Southeast Highlands (not shown). During July 1997 and 1999, a similar number of EMR events occur, 4 days vs. 3 days, respectively. Composite reanalyses of geopotential height and specific humidity at 700 hPa and 500 hPa show that, in the mean, the wind profile is from southerly-to- westerly with height (Fig. 3) over central Arizona and an axis of moist air is located eastward of Arizona, over western New Mexico (not shown). On such days, Arizona is positioned between a long-wave trough in the westerlies and the Bermuda High, lying within a transition zone between the drier air to the west and the more moist air to the east. It is likely that this transition zone is an example of the "monsoon boundary" described by Smith et al. (1989) and Adang and Gall (1989). Although terrain forcing and solar heating are likely important to storm development on such days, it is possible that other circulations, such as that associated with the monsoon boundary (Adang and Gall 1989) are significant contributors to the EMR. The EMR occurs most often following the DR, and signifies the beginning of the transition from days without storm development to days with storm development across central Arizona, owing, in part, to a moistening of the environment.

c. Central and eastern mountain regime (CEMR)

The CEMR is characterized by days where storms form mostly over the Mogollon Rim (not shown). Unlike the EMR, relative frequency maxima exist along the northwestern part of the Mogollon Rim (e.g. San Francisco Mountains) rather than along the southeastern part of the Mogollon Rim (e.g. White Mountains, Fig. 1). In addition, storm development over the Southeast Highlands is dominant later in the afternoon on CEMR days than on EMR days. Such differences in areas where storms tend to develop first are likely related to the earlier response to solar heating of higher elevations compared to lower elevations.

During July 1997, about half as many CEMR events occur than 1999 CEMR events; 4 events vs. 9 events, respectively. The CEMR occurs in 1997 and 1999 following all regime types except the DR. Composite upper-air analyses of geopotential height and specific humidity at 700 hPa and 500 hPa show that, in the mean, the wind profile is southerly-to-southwesterly with height over central Arizona and an axis of moist air located along the border between Arizona and New Mexico (not shown). Like EMR events, during CEMR events Arizona is positioned between a long-wave trough in the in the westerlies and the Bermuda High. However, on CEMR days, both the horizontal ridge-axis of the Bermuda High extends farther westward than during EMR events. Consequently, the transition zone between the drier air to the west and the more moist air to the east is shifted westward, and results in more moist mean conditions over central Arizona (not shown) than found during EMR events.

It is hypothesized that the mean flow pattern described above interacts with terrain in central and eastern Arizona, and with the aid of solar heating, provides the moisture, instability, and lift needed to support storm development in central and eastern Arizona. In addition, it is hypothesized that the focus of storm evolution over mountainous terrain without development over Phoenix and the Sonoran Desert may be due, in part, to the southerly to southwesterly steering level winds (700–500 mb) that mitigate storm movement from higher-to-lower elevations (not shown). Such hypotheses will be addressed in future modeling studies.

d. Central, eastern, and Phoenix regime (CEPR)

The CEPR is characterized by the development of convective storms over the Mogollon Rim and Southeast Highlands during the early afternoon, the movement and redevelopment of storms from higher terrain toward the lower terrain of the Sonoran Desert during the late afternoon, and the movement and redevelopment of storms into the Sonoran Desert and Phoenix during the evening (not shown). This regime is similar to the evolution of storms depicted by studies of Arizona's diurnal climatology (Balling and Brazel 1987; King and Balling 1994; Watson et al. 1994b). During July 1997 and 1999, a similar number of CEPR events occur, 7 days vs. 8 days, respectively. Interestingly, storms that develop and/or move into Phoenix during July 1997 tend to be more isolated and shorter-lived than storms that develop and/or move into Phoenix during July 1999.

To determine possible causes for the lesser amount of storm development in Phoenix during CEPR events in 1997 compared to 1999, composite reanalyses and Phoenix soundings are created separately for CEPR events in July 1997 and July 1999, and compared subjectively. Examination of composite reanalyses of geopotential height and specific humidity at 700 hPa and 500 hPa show that, during July 1997, the mean wind profile at Phoenix turns from southeasterly to southerly and an axis of moist air is located in western New Mexico (Figs. 2, 3). In contrast, during July 1999 the mean wind profile in Phoenix turns from easterly to southerly, and an axis of moist air is located along the border between Arizona and New Mexico rather than over western New Mexico (Figs. 2, 3). Consequently, the July 1999 composite sounding at Phoenix is more moist, contains more Convective Available Potential Energy (CAPE), and less Convective Inhibition (CIN) than the associated July 1997 sounding. It is suggested that the higher frequency and larger areal coverage of storm development in Phoenix during July 1999 may be supported, in part, by the combined effects of relatively moist air, higher CAPE values, and lower CIN values in the presence of easterly steering-level flow.

e. Widespread regime (WR)

The WR is characterized by days where storms occur over most of central Arizona (not shown). This WR is present during July 1999 only, and is comprised of 3 events where storms develop first over southern Arizona and move northward, 2 events where storms develop first over western Arizona and move eastward, and 1 event where storms develop first over eastern Arizona and move westward. The relation of the 2 west-to-east moving events to approaching longwave troughs and/or shortwave troughs in the westerlies agrees with previous studies of burst events by Carleton (1986) and Watson et al. (1994a). Since widespread events associated with shortwave troughs in the westerlies have been examined previously, this section will focus in widespread events that develop progressively from the south toward the north.

Composite upper-air analyses of geopotential height and specific humidity at 700 hPa and 500 hPa show that, in the mean, the wind profile is southeasterly over central Arizona and an axis of moist air is located over central-to-eastern Arizona (not shown). On such days, Arizona is positioned between a high-amplitude, slightly-negatively tilted long-wave trough in the westerlies and the Bermuda High, whose horizontal ridge axis extends westward to the border between Arizona and New Mexico. A potential mechanism for storm development that merits further investigation is the forcing associated with easterly waves that occasionally move westward over the southern Gulf of California and have been linked to surges of moisture in the Gulf of California (e.g., Stensrud 1997; Fuller and Stensrud 2000). Indeed, the expanse of the moist axis from the Gulf of California through central Arizona suggests that a low-level jet may be the mechanism responsible for the westward shift in the moist axis. The composite 12 UTC sounding at Phoenix shows that the atmosphere contains the high precipitable water, CAPE, and instability values conducive to storm development (not shown).

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REFERENCES Available upon request or at http://www.nssl.noaa.gov/~mackeen/prospectusweb.htm, where figures not shown and new results from this study are updated periodically.

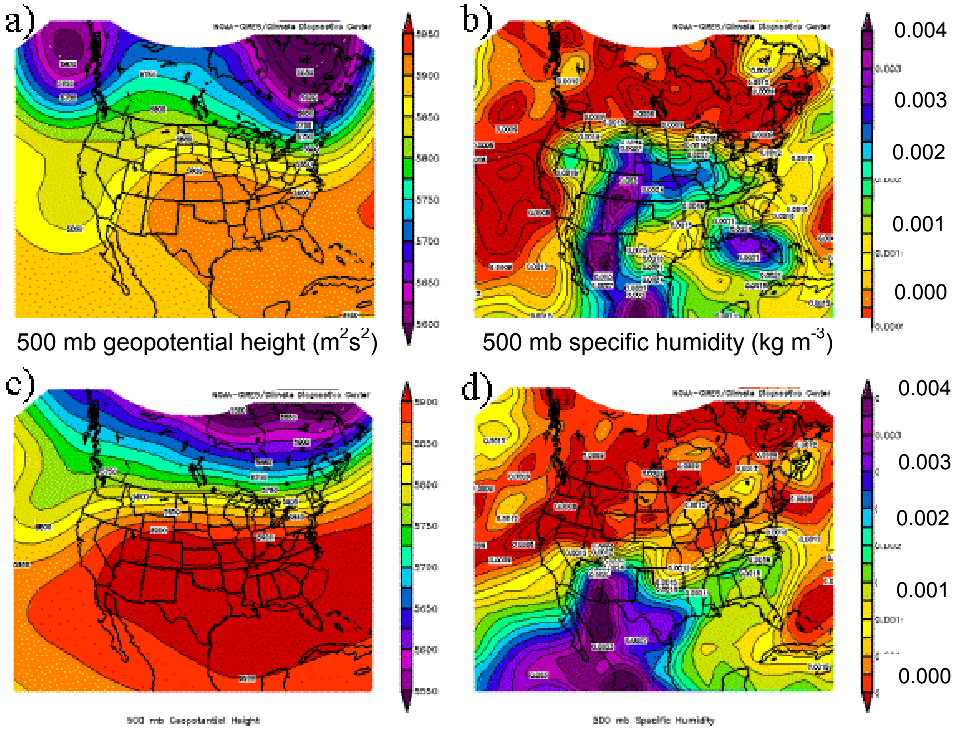

Figure 2. July 1997 12 UTC composite 500-mb (a) geopotential height and (b) specific humidity for the 7 central, eastern, and Phoenix regime (CEPR) events. July 1999 12 UTC composite 500-mb (c) geopotential height and (d) specific humidity for the 8 CEPR events.

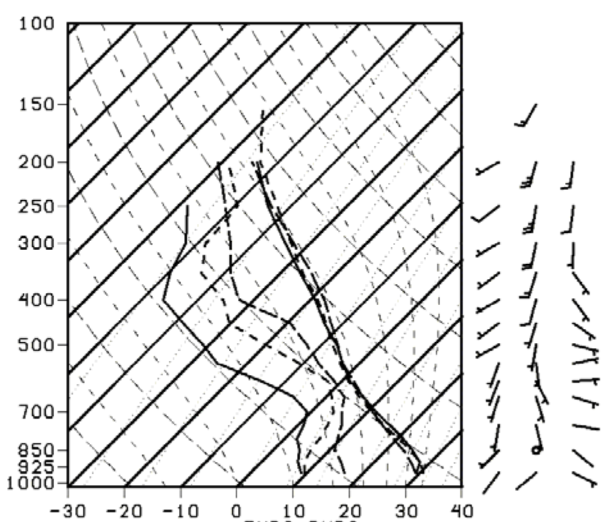

Figure 3. Composite Phoenix sounding at 12 UTC for (1) eastern mountain regime during July 1997 and 1999 (solid line and left-most wind profile), (2) central, eastern, and Phoenix regime during July 1997 (short-dashed line and center wind profile), and (3) central, eastern, and Phoenix regime during July 1999 (long-dashed line and right-most wind profile).