Intraseasonal Variability of Summer Storms over central Arizona
during 1997 and 1999

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Abstract

Although previous climatologies over central Arizona show a summer diurnal precipitation cycle, daily storm development deviates from this periodicity. The purpose of this study is to investigate the intraseasonal variability of diurnal storm development over Arizona during the 1997 and 1999 North American Monsoons (NAMs). Radar reflectivity mosaics constructed from Phoenix and Flagstaff Weather Surveillance Radar-1988 Doppler (WSR-88D) reflectivity data reveal five repeated storm development patterns or regimes. The diurnal evolution of each regime is illustrated by computing frequency maps of reflectivity 25 dBZ and greater during 3-h periods. The first regime is indicated by a lack of rainfall over the domain (dry regime, DR). The second is characterized by storm development over mountainous terrain in eastern Arizona only (eastern mountain regime, EMR), whereas the third is characterized by storm development over both mountainous terrain in eastern Arizona and the Mogollon Rim (central–eastern mountain regime, CEMR). The fourth regime is similar to the summertime diurnal climatology, where storms develop initially over both the Mogollon Rim and mountains of eastern Arizona, and later move toward lower elevations, culminating in the Sonoran Desert (central–eastern mountain and Sonoran regime, CEMSR). The final regime is characterized by organized storm development that is tied less strongly to the diurnal cycle (nondiurnal regime, NDR). The tendency for repeated storm development over different geographic regions suggests that storm growth is tied strongly to terrain forcing and the synoptic-scale environment.
1. Introduction

Over 63% of Arizona’s 5.13 million residents live in Phoenix–Mesa, a metropolitan area with an explosive population growth of 45.3% between 1990 and 2000 (http://www.census.gov). With this rapidly growing population, potential impacts from summertime convective storms are increasing. Socio-economic impacts from storms can include damage to property and threat to life from high winds, flash flooding, and/or lightning (Sellers and Hill 1974; Hales 1975; Schmidli 1986). Additionally, downed power lines from high winds can result in loss of profits to power companies (Dempsey et al. 1998), disruption to life and businesses, and transportation delays. Although summer storms are sometimes hazardous, farmers and cattle ranchers depend on storm runoff to keep their vegetation thriving (Jurwitz 1953; Sellers and Hill 1974). Because Arizona receives up to 50% of its annual rainfall from summer storms, improved understanding of intraseasonal variability of storm development and associated environmental conditions are important to public safety and economics.

Arizona’s summer wet season occurs in response to the North American Monsoon (NAM), a reversal in circulation at low and midlevels over Mexico and the Desert Southwest every July and August (e.g., Douglas et al. 1993; Adams and Comrie 1997). During this wet season, precipitation exhibits a diurnal cycle. Arizona’s summertime diurnal precipitation climatology is forced primarily by mountainous terrain surrounding the Sonoran Desert (Fig. 1). In the morning, storms tend to initiate over the Mogollon Rim, White Mountains, and Southeast Highlands. During the afternoon, storms tend to move southward down the Mogollon Rim and southwestward from the White Mountains and Southeast Highlands, culminating in the Sonoran
Desert near sundown. This evolution is ubiquitous: it appears in diurnal climatologies using precipitation-gauge (Balling and Brazel 1987), lightning (Watson et al. 1994a; King and Balling 1994) and radar reflectivity data (Hales 1972; MacKeen and Zhang 2000). Despite this robust diurnal precipitation cycle, tremendous intraseasonal variations in the occurrence, timing, and location of convective storms are possible.

Historically, intraseasonal variations in Arizona’s precipitation during the NAM are categorized as wet and dry periods, or “bursts” and “breaks,” respectively (Carleton 1986; Watson et al. 1994b; Mullen et al. 1998). Such simple stratifications of precipitation, however, fall short of capturing the variety of observed precipitation patterns over central Arizona. To date, Wallace (1997) and Wallace et al. (1999) provide the most detailed study of intraseasonal variability of precipitation by using lightning data to substratify wet periods in Phoenix into convective and nonconvective events. Since 1997, the availability of Weather Surveillance Radar-1988 Doppler (WSR-88D) radar data at Phoenix and Flagstaff affords an opportunity to investigate intraseasonal variability of precipitation at higher temporal and spatial resolution than lightning- (Watson et al. 1994b; Wallace 1997; Wallace et al. 1999), satellite- (Carleton 1986), or precipitation-gauge-based studies (Mullen et al. 1998).

Because model predictions of precipitation verify poorly during Arizona’s warm season (Dunn and Horel 1994; Bright and Mullen 2002), a better understanding of intraseasonal variability of precipitation during the NAM may lead to improved regional forecasts of storm likelihood that may, in turn, help residents and businesses prepare better for possible threats to life, damage to property, and loss of profit. Therefore, the purpose of this paper is to investigate the
variety of diurnal storm development patterns over much of the Sonoran Desert and surrounding mountainous terrain (Fig. 1) during two NAM seasons. By using WSR-88D radar reflectivity data, investigation of diurnal storm development situations is based on temporal and spatial resolutions more similar to those faced by forecasters. As described in section 2 and the appendix, radar reflectivity data from both the Phoenix and Flagstaff WSR-88Ds are combined to produce a mosaic of reflectivity fields with spatial continuity over mountainous terrain between these sites. Section 2 also describes the methodology used to identify the five repeated storm development regimes found in this study. Distinguishing diurnal characteristics of each regime are illustrated in section 3. The summary and conclusions are given in section 4. A companion paper (Heinselman and Schultz 2004) examines the role of synoptic-scale flow in controlling the occurrence of these radar-based storm development patterns.

2. Radar data and methodology

This section describes the data and methodology used to study the variety of diurnal summer storm development over central Arizona. Diurnal storm development is defined as both the initiation and subsequent evolution of storms occurring each day. First, we present the radar data and objective analysis techniques used to construct high-resolution reflectivity mosaics. Second, we show how these reflectivity mosaics are used to assess intraseasonal variability of diurnal storm development during the NAM.

The intraseasonal variability of diurnal storm development patterns is investigated using WSR-88D level II radar reflectivity data only from the Phoenix (KIWA) and Flagstaff
(KFSX) sites (Fig. 1) during two NAM seasons, July and August 1997 and 1999, respectively. The choice of these periods arose from three considerations. First, the analysis period begins in 1997 because it marks the first year where radar data are available from both the Phoenix and Flagstaff WSR-88D sites. Second, because a related study (Heinselman and Schultz 2004) is concerned with the associated variability of the tropospheric environment at Phoenix, the 1998 summer season is excluded owing to large gaps in archived sounding data. Third, analyses span from July through August because precipitation associated with the NAM usually begins in early July, and dissipates during September (Sellers and Hill 1974). During these periods, WSR-88D data are available and analyzed for 112 of the 124 days (~90% of events), with 10 days (2 days) missing from the 1997 (1999) dataset. Because this study examines two NAMs only, the true extent of the intraseasonal variety of diurnal storm development patterns may not be captured. Nevertheless, this study provides the first examination of these patterns using high-resolution radar reflectivity data.

Radar data from KIWA and KFSX are quality controlled to minimize echo from nonmeteorological sources, as detailed in the appendix. Data from these two radars are then combined to produce a single product termed the composite mosaic grid, aimed at minimizing radar data limitations and composing a more complete depiction of precipitation than either radar alone could provide (Zhang et al. 2004). Composite mosaics are a two-dimensional field of maximum reflectivity values within each column of reflectivity data (1-km x 1-km x 12 km) that are created every 10 min. The details of the mosaic process are also discussed in the appendix.
The variety of diurnal storm development patterns that evolve during 1997 and 1999 is investigated by examining manually the spatial and temporal characteristics of diurnal storm development over central Arizona for all 112 days (a day is defined as the 24-h period beginning at 12 UTC). To expedite this process, hourly frequencies of composite mosaics of reflectivity 25 dBZ and higher are calculated beginning at the top of each hour. The 25-dBZ threshold serves as a proxy for storm occurrence. Next, hourly frequencies of reflectivity 25 dBZ and higher are displayed on a high-resolution terrain map (1-km x 1-km spacing), animated, and analyzed manually to assess the defining spatial and temporal characteristics of diurnal storm occurrence. Defining characteristics are designed to reflect forecast concerns: the timing and location of storm initiation (i.e., first occurrence of nonzero frequencies and their spatial extent), locations of subsequent storm development, and the timing and location of storm demise (i.e., the last occurrence of nonzero frequencies and their spatial extent). This manual assessment provided an in-depth knowledge of each day’s initial and subsequent storm evolution unattainable by automated techniques.

During this examination, differences among defining characteristics became apparent on several days during the 1997 and 1999 NAMs. For example, on some days, initial storm occurrence was tied to mountainous terrain in eastern Arizona with subsequent storm occurrence limited to the eastern third of the domain. On other days, initial and subsequent storm occurrence extended across the entire Mogollon Rim. Still, on some days, initial storm occurrence not only extended across the Mogollon Rim and subsequently progressed toward lower elevations to the south, but also culminated over the Sonoran Desert. These differences in the defining characteristics of diurnal storm occurrence form the basis of our classification. The grouping of days
with similar defining characteristics reveals five repeated diurnal storm occurrence regimes (Table 1 and Fig. 2). Naturally, there are discrepancies in the details among days with similar defining characteristics. Nevertheless, the events fit easily into one of the five regimes with little ambiguity, implying some robustness to this classification. Differences in the defining characteristics of the five regimes are illustrated by computing diurnal 3-h frequencies (e.g., 12–14 UTC, 15–17 UTC, 18–20 UTC) of composite radar reflectivity, 25 dBZ and higher, from the 10 min mosaics for days comprising each regime. The spatial and temporal characteristics of each regime’s frequency maps are described below.

3. Radar reflectivity regimes

Five repeated storm development regimes are found over the domain (Table 1 and Fig. 2). Figure 2 shows the temporal evolution of these regimes. Based on the defining characteristics, relative frequencies of composite reflectivity evolve repeatedly over similar geographic regions in central Arizona in four of the five regimes, including: 1) eastern mountains (called eastern mountain regime: EMR; 11 days or 9% of events), 2) central and eastern mountains (called central–eastern mountain regime: CEMR; 39 days or 31.5% of events), 3) central mountains, eastern mountains, and Sonoran Desert (called central–eastern mountain and Sonoran regime: CEMSR; 17 days or 14% of events), and 4) none of the domain (called dry regime: DR; 13 days or 10.5% of events).

The fifth regime is distinguished by storm development that is less closely tied to the climatological diurnal cycle, and therefore is called the nondiurnal regime (NDR). Such events
occur on 27 days, or 22% of the time, and are depicted by organized storms that move across Arizona with the prevailing steering-level flow, including westerlies, easterlies, and southerlies. Owing to such differences in storm movement, days within this regime are subcategorized according to direction of storm movement, including northward moving (NDR-N; 13 days or 48% of NDR events), eastward moving (NDR-E; 8 days or 30% of NDR events), and westward moving (NDR-W; 6 days or 22% of NDR events). Five days or 4% of events occur over various isolated areas in central Arizona (called unclassified), and twelve days or approximately 10% of the radar dataset are missing. Both unclassified and missing events are excluded hereafter, such that 107 of 124 possible events are examined.

As described in Section 2b, each regime’s diurnal storm evolution is illustrated by computing 3-h frequencies of composite radar reflectivity during the period of peak storm development (i.e., 18–09 UTC; LST = UTC – 7 h). The resulting regimes exemplify the defining characteristics of the variety of diurnal storm development regimes over central Arizona during the 1997 and 1999 NAMs.

a. Eastern mountain regime (EMR)

The eastern mountain regime is characterized by storm development over the mountains of eastern Arizona. Storms develop first in the vicinity of the White Mountains and the Southeast Highlands in the early afternoon (18–20 UTC; Fig. 3a). By mid afternoon, the areal extent of storm development is maximized, as storms begin to move toward lower elevations (22–00 UTC; Fig. 3b). Toward evening, storm development is most frequent over the Southeast
Highlands (02–04 UTC; Fig. 3c), and, by early morning, storm development has ceased (06–08 UTC; Fig. 3d).

Compared to other precipitating regimes, EMR occurs least frequently (only 9% of the time) and evolves over the smallest geographic region. Also, EMR’s frequencies of radar reflectivity are comparatively low. These lower frequencies may result, in part, from radar beam blockage over the Southeast Highlands. Additionally, lower frequencies may indicate high spatial and temporal variability in storm development within a relatively small sample size.

b. Central–eastern mountain regime (CEMR)

The central and eastern mountain regime is characterized by storm development over the Mogollon Rim, White Mountains, and Southeast Highlands (Fig. 4). Storms develop first over the peaks of the Southeast Highlands and the higher elevations of the Mogollon Rim, such that a linear frequency pattern extends from the White Mountains to the San Francisco Mountains (18–20 UTC; Fig. 4a). Like EMR, by mid afternoon, the areal extent of storm development is maximized as storms begin to move toward lower elevations (22–00 UTC; Fig. 4b). Toward evening, the areal extent of storm development over the Mogollon Rim is greatly diminished, while storms continue to move away from the Southeast Highlands (02–04 UTC; Fig. 4c). By early morning, storms infrequently occur over the Southeast Highlands and White Mountains (06–08 UTC; Fig. 4d).
Compared to other regimes, CEMR occurs most frequently (31.5%), demonstrating the environment’s propensity for storm development over mountainous terrain. The major difference between EMR and CEMR is the expanded storm development across the Mogollon Rim and larger areas of higher frequencies (3–5% vs. 7–14%, respectively) of radar reflectivity over mountainous terrain (cf. Figs. 3 and 4).

c. Central–eastern mountain and Sonoran regime (CEMSR)

CEMSR is characterized by initial storm development over the Mogollon Rim, Southeast Highlands, and Central Mountains and later development over the Sonoran Desert (Fig. 5). Storms develop first over higher elevations of the San Francisco Mountains, Mogollon Rim, White Mountains, Southeast Highlands, and Central Mountains during the early afternoon (18–20 UTC; Fig 5a). This early afternoon storm development is more widespread over mountainous terrain compared to CEMR and EMR. There is a tendency also for higher frequencies of radar reflectivity during CEMSR than CEMR along the Mogollon Rim (11–14% vs. 7–10%, respectively) and in the vicinity of the White Mountains and San Francisco Mountains (15–18% vs. 7–10%, respectively; cf. Figs. 4a and 5a). By mid afternoon this region of frequencies expands to the north and south, and its magnitude intensifies along the ranges of the Central Mountains (20–00 UTC; Fig. 5b). Compared to CEMR, this band of high frequencies is more distinct and intense, and frequencies of radar reflectivity are higher and more widespread along the periphery of the Sonoran Desert (cf. Figs. 4b and 5b). This more intense band of high frequencies, compared to CEMR, reflects the tendency for more organized storm development during CEMSR.
Unlike EMR and CEMR, during CEMSR, storm occurrence is abundant over the Central Mountains, Southeast Highlands, and the Sonoran Desert toward evening (02–04 UTC; cf. Figs. 3c, 4c, and 5c), with secondary frequency maxima in the vicinity of the Southeast Highlands and southwestern and western parts of the Sonoran Desert. By early morning, storm development is diminished over the Central Mountains but remains somewhat active over the Southeast Highlands and the Sonoran Desert (Fig. 5d). The storm evolution of this regime is similar to that depicted by Arizona’s diurnal climatology, capturing both the afternoon precipitation maxima over mountainous terrain and the late night precipitation maxima over the Sonoran Desert (Balling and Brazel 1987; King and Balling 1994; Watson et al. 1994a). Since three of the four precipitating regimes involve storm development over mountainous terrain during the afternoon, the similarity between EMR, CEMR, CEMSR, and climatology is hardly surprising.

CEMSR occurs about half as frequently as CEMR (14% vs. 31.5%, respectively), indicating that ingredients for storm occurrence are present in the Sonoran Desert less often than over mountainous terrain. The major difference between CEMSR and CEMR during the afternoon is more frequent storm development across the Mogollon Rim, Southeast Highlands, and Central Mountains surrounding the Sonoran Desert in CEMSR.

d. Nondiurnal regime (NDR)

The nondiurnal regime (NDR) is characterized by storm development that is tied less strongly to the topographically influenced diurnal precipitation cycle than the previous three regimes (EMR, CEMR, and CEMSR; cf. Figs. 3–6). Although frequencies of radar reflectivity
show early afternoon storm development over higher terrain, including western portions of the Central Mountains and Mogollon Rim, and most of the Southeast Highlands, storms may also occur over the Painted and Sonoran Deserts (18–20 UTC; Fig. 6a). By mid afternoon, storm development is most frequent the Sonoran Desert (maximum of 19–22%), and less frequent over most of the Mogollon Rim, Central Mountains, Southeast Highlands, and Painted Desert (22–00 UTC; Fig. 6b). Afternoon storm occurrence over the Sonoran is an identifying characteristics because, climatologically, storms usually occur over this region at night. By early evening, storm development is most frequent over the Sonoran Desert and Southeast Highlands (11–14%), with lower frequencies over the Central Mountains, Mogollon Rim, and Painted Desert (3–10%; 02–04 UTC; Fig. 6c). In the early morning, storm development is most frequent over regions within the Central Mountains and Painted Desert (7–10%), and infrequent over most of the Sonoran Desert and Southeast Highlands (06–08 UTC; Fig. 6d). Although NDR’s diurnal cycle of reflectivity frequency highlights the development of afternoon storms over the Sonoran Desert, on a given day, storm development can differ markedly from that described above. Oftentimes, storm development is organized in linear convective lines (Smith and Gall 1989) or evolves into a mesoscale convective system (MCS; McCollum et al. 1995). Variations in diurnal storm development arise, in part, owing to variability in storm movement, which may be categorized as northerly, easterly, or westerly on each day.

\[ e. Precipitation over Phoenix–Mesa \]

Of the five regimes described above, only two impact Phoenix–Mesa: CEMSR and NDR. To validate rainfall at the surface underneath radar echoes within Phoenix–Mesa and the
surrounding area during NDR and CEMSR, and a lack thereof during DR, EMR, and CEMR, distributions of 24-h rainfall data associated with each regime are examined. Owing to the societal impacts of summer storms on high-population areas, we chose observations of 24-h rainfall obtained from the Automated Local Evaluation in Real Time (ALERT) rain-gauge network (http://www.fcd.maricopa.gov/Services/ALERT) within Phoenix–Mesa and the surrounding desert (Fig. 1). This region is chosen also for its high density of rain gauges (75 in 1997 and 96 in 1999). The associated domain extends latitudinally 32.83°N–33.76°N, and longitudinally 111.39°W–113.12°W (Fig. 1).

Validation of rainfall, or a lack thereof, begins by ranking ALERT observations from lowest to highest 24-h precipitation amounts for all days within each regime. Owing to a relatively small number of nonzero values found in each regime’s ranked rainfall data, differences in measurable rainfall amounts are made more discernible by computing percentiles of 24-h rainfall amounts associated with each regime (0.05–0.95; Fig. 7). As expected, no measurable precipitation is reported within the ALERT network during DR or EMR (not shown). During CEMR, 5% of precipitation values at all stations are nonzero (Fig. 7). In contrast, 30% and 35% of precipitation values are nonzero during NDR and CEMSR, respectively. Moreover, 4.8 (2.6) times more stations reported nonzero 24-h accumulated precipitation during NDR (CEMSR) than CEMR. Furthermore, the top 5% of 24-h precipitation values during NDR and CEMSR are about ten times higher than those reported during CEMR, at 10.9 mm and 13.0 mm, respectively. In conclusion, the relative lack of 24-h accumulated precipitation over Phoenix–Mesa and the surrounding area corroborates the absence of relative frequencies of reflectivity during DR, EMR, and CEMR, compared to CEMSR and NDR.
4. Summary and conclusions

This study finds intraseasonal variability in precipitation over central Arizona during the summers of 1997 and 1999 is more complex than the simple binary burst and break periods from previous studies (e.g., Carleton et al. 1986; Watson et al. 1994a; Mullen et al. 1998). An examination of the diurnal characteristics of relative frequencies of reflectivity 25 dBZ and higher reveals five storm development patterns, or regimes. First, the dry regime (DR) is indicated by a lack of rainfall across the domain. Second, the eastern mountain regime (EMR) is indicated by storm development over the mountains of eastern Arizona, especially the Southeast Highlands and White Mountains. Third, the central–eastern mountain regime (CEMR) is characterized by storm development over both the mountains of eastern and central Arizona, including the Southeast Highlands, White Mountains, Mogollon Rim, and Central Mountains. Fourth, the central–eastern mountain and Sonoran regime (CEMSR) is characterized by early afternoon storm development over the eastern and central mountains of Arizona that moves toward lower elevations in the afternoon, and culminates over the Sonoran Desert in the evening and night hours. Finally, the nondiurnal regime (NDR) consists of organized storm development that may not follow the diurnal cycle and tends to move with the steering-level flow.

Regimes with higher areal storm coverage (CEMR, CEMSR, and NDR) represent the variety of diurnal storm development observed during bursts and account for 67.5% of events, whereas regimes with lower areal storm coverage (DR and EMR) represent the variety of diurnal storm development observed during breaks and account for 19.5% of events. The remaining 13% of events are either unclassified or missing. The temporal evolution of regimes (Fig. 2)
indicates that bursts began later in July during 1997 than 1999 and that breaks were short-lived compared to bursts (1–3 days vs 2–18 days, respectively). These characteristics of temporal variability in bursts and breaks are similar to those found by Watson et al. (1994a). Of greater interest to the forecaster may be the temporal variability of each regime and the relation of this variability to the synoptic-scale flow, a topic addressed in Heinselman and Schultz (2004).

Two of the three burst regimes, CEMSR and NDR, produce rainfall over the Sonoran Desert and oftentimes Phoenix–Mesa as well. The tendency for CEMSR and NDR to produce precipitation over this metropolis and the surrounding desert was validated using the ALERT gauge network. On some days, storm occurrence diminishes just before moving off the mountains and into Phoenix–Mesa. In retrospect, these situations are classified as CEMR, but, as noted by forecasters at the Phoenix National Weather Service Forecast Office, they can be difficult to forecast ahead of time. Both the present study and Wallace (1997) indicate a tendency for greater frequency of storm development over the mountainous terrain surrounding the Sonoran Desert prior to precipitation over Phoenix. This tendency may prove useful as a nowcast tool for forecasters.

Repeated storm development over the Mogollon Rim, Southeast Highlands, and Central Mountains illustrates the importance of terrain forcing in the initiation of moist convection in Arizona during the summer. Differences in geographic regions where storms develop repeatedly suggest that corresponding variations in environmental conditions and the synoptic-scale flow may exist which help discern one regime from another. This hypothesis is addressed in
Heinselman and Schultz (2004), who examine and compare characteristics of composite upper-air maps and 12 UTC soundings at Phoenix associated with these regimes.

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**APPENDIX**

Quality Control, Adaptive Barnes Interpolation, and Mosaic Technique

Quality control techniques are applied to minimize echo from nonmeteorological sources, including ground clutter and anomalous propagation. In this quality control process, a bin of radar reflectivity is considered ground clutter if its height is below the height of the hybrid reflectivity level (Gourley et al. 2001). The hybrid reflectivity level is defined as the height where one of the four lowest radar tilts is at least 50 m (164 ft) above ground level (see Fig. A1 for heights of the KIWA and KFSX hybrid scan). As illustrated in Fig. A1, the height of the hybrid reflectivity level increases most quickly with increasing range from the radar in regions where terrain blocks the radar beam. Thus, within radials of rapid increases in the height of the radar beam, the lowest elevation angle of KIWA or KFSX may overshoot storm top.
A radar reflectivity observation is considered anomalous propagation, or surface-ducting of the radar beam, if it is nearly stationary (corresponding velocity magnitude is 2.5 m s\(^{-1}\) or less) and the magnitude of the reflectivity value above the observation is comparatively small (Gourley et al. 2001). Specifically, significant decreases in reflectivity with height are considered nonmeteorological if the reflectivity value within a bin at the tilt just above the hybrid tilt height is at least 90% lower than the reflectivity value within a corresponding bin at the hybrid tilt height (Gourley et al. 2001). Radar reflectivity data identified as ground clutter or anomalous propagation are removed from the data set.

Following data quality control, the radar-coordinate radar reflectivity volumes from each radar are interpolated to a three-dimensional Cartesian grid by performing an adaptive Barnes interpolation scheme (e.g., Askelson et al. 2000; Trapp and Doswell 2000). The details of the employed scheme are described below. The Cartesian grid has a cylindrical equidistant latitude/longitude reference frame, such that only distance along standard parallels and meridians are true to scale. The Cartesian grid is 440 km x 440 km in the horizontal dimension (Fig. 1), with 1-km grid spacing 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 raw reflectivity factor, \( f_r \), is interpolated from radar coordinates, \( f_r(r, \Theta, \phi) \), to Cartesian coordinates, \( f_g(x, y, z) \), by performing an adaptive Barnes interpolation scheme (e.g., Askelson et al. 2000; Trapp and Doswell 2000):
where the weighting factor $w_i$ is defined as:

$$w_i = \exp\left[-\frac{(r_g - r_i)^2}{\kappa_r} - \frac{(\theta_g - \theta_i)^2}{\kappa_\theta} - \frac{(\phi_g - \phi_i)^2}{\kappa_\phi}\right],$$

where $r, \theta, \phi$ represent polar coordinates of distance, azimuth, and elevation, $x, y, z$ represent Cartesian coordinates of horizontal distance and height, the subscript $i$ represents a bin of raw reflectivity data in polar coordinates, the subscript $g$ represents a grid point of interpolated reflectivity data in Cartesian coordinates, $N$ is the number of radar bins influencing the interpolated grid value, and $\kappa_r, \kappa_\theta, \kappa_\phi$ are the dimensional filtering parameters. These dimensional filtering parameters are a function of $r$ only, and are defined in appendix A of Heinselman (2004).

The influence region of $f_g(x,y,z)$ is volumetric and defined in polar coordinates, such that radar bins located within 5-km radial distance, 2° azimuth, and within the two closest elevation scans above and below the grid point, contribute toward that point’s weighted reflectivity value. Since the resolution of radar reflectivity data decreases in azimuthal and vertical directions with increasing range from the radar, the region of influence applied to grid points located far from the radar is larger than the region of influence applied to grid points located near the radar. In both situations, the region of influence includes the same number of data points. Since azi-
muthal- and elevation-length scales increase with increasing range, filtering \( \kappa_\theta(r) \) and \( \kappa_\phi(r) \) is range-dependent in these dimensions (Heinselman 2004).

Once each volume scan of reflectivity from the KIWA and KFSX radars is interpolated to the Cartesian grid, a three-dimensional reflectivity mosaic is created by combining radar data at each Cartesian level \( z \). Use of two radars minimizes radar data limitations such as beam blockage and decreasing resolution with increasing range, and composes a more complete depiction of storm structure and precipitation than either radar alone could provide. At each level \( z \), interpolated reflectivity values, \( f_g(x, y, z) \), are mosaicked to each grid point, \( f_m(x, y, z) \), in the domain using an inverse distance-weighted average (Zhang et al. 2004):

\[
f_m(x, y, z) = \frac{\sum_{n=1}^{n_{\text{radars}}} w_n(x, y, z) f_g^n(x, y, z)}{\sum_{n=1}^{n_{\text{radars}}} w_n(x, y, z)},
\]

where \( n_{\text{radars}} \) is the number of radars that cover each grid point (\( n_{\text{radars}} = 2 \)), \( f_g^n(x, y, z) \) is the interpolated reflectivity value from the \( n_{\text{th}} \) radar, and \( f_m(x, y, z) \) is the mosaicked value at each grid point. The weight, \( w_n \), given to a radar observation is dependent on the distance between the radar and the observation (i.e., Cressman weight function; Zhang et al. 2004):

\[
w_n(x, y, z) = \frac{R_{\text{inf}}^2 - d_n^2(x, y, z)}{R_{\text{inf}}^2 + d_n^2(x, y, z)},
\]
where $R_{inf}$ is the farthest range at which a valid observation is attainable ($R_{inf} = 300$ km), and $d_n(x,y,z)$ is the distance between a mosaic grid point and the $n_{th}$ radar. The final three-dimensional radar reflectivity mosaic is created every 10 min. A composite reflectivity mosaic is also computed, which compresses the three-dimensional Cartesian grid to a two-dimensional field of maximum reflectivity value within each 1-km x 1-km x 12-km column.
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Figure 1. Elevation (m) of terrain features in domain, gridded at 1-km resolution from 30 arc-sec USGS data. Also shown are locations of WSR-88D sites (yellow triangles), rawinsonde sites (orange circles), cities (pink circles), and terrain features (green letters). The light blue box denotes the regional extent of the Automated Local Evaluation in Real Time (ALERT) Network of rain gauges used in this study.

Figure 2. Temporal distribution of regimes during the 1997 and 1999 NAMs. NDR denotes the nondiurnal regime, CEMSR denotes the central–eastern mountain and Sonoran regime, CEMR denotes the central–eastern mountain regime, UNC denotes unclassified days (indicated by small dot), EMR denotes the eastern mountain regime, and DR denotes the dry regime. Days missing radar data (MISS) are left blank.

Figure 3. Three-h frequencies of radar reflectivity 25 dBZ and higher for the eastern mountain regime (EMR) at (a) 18–20 UTC, (b) 22–00 UTC, (c) 02–04 UTC, and (d) 06–09 UTC.

Figure 4. Same as in Fig. 3, except for the central–eastern mountain regime (CEMR).

Figure 5. Same as in Fig. 3, except for the central–eastern mountain and Sonoran regime (CEMSR).

Figure 6. Same as in Fig. 3, except for the nondiurnal regime (NDR).

Figure 7. Ranked distribution by percentile of all 24-h precipitation totals (mm) from the ALERT network associated with CEMR (denoted by circles; N=3429), CEMSR (denoted by diamonds;
N=1485), and NDR (denoted by X; N=2361). In 1997 (1999), the ALERT network contained 71 (96) stations.

Table 1. Distribution of reflectivity regimes during the 1997 and 1999 NAMs, where DR is the dry regime, EMR is the eastern mountain regime, CEMR is the central–eastern mountain regime, CEMSR is the central–eastern mountain and Sonoran Desert regime, NDR is the nondiurnal regime, UNC is the unclassified regime, and MISS is days missing from the radar dataset. Shaded columns highlight the two regime types that occur most frequently in 1997 and 1999.

Figure A1. Height of hybrid scan, or lowest elevation above 50 m (164 ft), where data are collected for KIWA and KFSX WSR-88Ds (m AGL; courtesy of Jian Zhang). The thick white box denotes this study’s domain.
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<th>EMR</th>
<th>CEMR</th>
<th>CEMSR</th>
<th>NDR</th>
<th>UNC</th>
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<td>5</td>
<td>15</td>
<td>7</td>
<td>11</td>
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<td>10</td>
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<td></td>
<td>(15%)</td>
<td>(8%)</td>
<td>(24%)</td>
<td>(11%)</td>
<td>(18%)</td>
<td>(8%)</td>
<td>(16%)</td>
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<tr>
<td>July–August 1999</td>
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<td>6</td>
<td>24</td>
<td>10</td>
<td>16</td>
<td>0</td>
<td>2</td>
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<tr>
<td></td>
<td>(6%)</td>
<td>(10%)</td>
<td>(39%)</td>
<td>(16%)</td>
<td>(26%)</td>
<td>(0%)</td>
<td>(3%)</td>
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<tr>
<td>Total</td>
<td>13</td>
<td>11</td>
<td>39</td>
<td>17</td>
<td>27</td>
<td>5</td>
<td>12</td>
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<tr>
<td></td>
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<td>(9%)</td>
<td>(31.5%)</td>
<td>(14%)</td>
<td>(22%)</td>
<td>(4%)</td>
<td>(9%)</td>
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Figure 1. Elevation (m) of terrain features in domain, gridded at 1-km resolution from 30 arc-sec USGS data. Also shown are locations of WSR-88D sites (yellow triangles), rawinsonde site (orange circles), cities (pink circles), and terrain features (green letters). The light blue box denotes the regional extent of the Automated Local Evaluation in Real Time (ALERT) network of rain gauges used in this study.
Figure 2. Temporal distribution of regimes during the 1997 and 1999 NAMs. NDR denotes the nondiurnal regime, CEMSR denotes the central–eastern mountain and Sonoran regime, CEMR denotes the central–eastern mountain regime, UNC denotes unclassified (indicated by small dot), EMR denotes the eastern mountain regime, and DR denotes the dry regime. Days lacking radar data are left blank.
Figure 3. Three-h frequencies of radar reflectivity 25 dBZ and higher for the eastern mountain regime (EMR) at (a) 1800–2000 UTC, (b) 2200–0000 UTC, (c) 0200–0400 UTC, and (d) 0600–0800 UTC.
Central–Eastern Mountain Regime (CEMR)

(a) 1800 – 2000 UTC
(b) 2200 – 0000 UTC
(c) 0200 – 0400 UTC
(d) 0600 – 0800 UTC

Relative frequency of reflectivity $Z > 25$ dB

Legend:

- 0 - 2%
- 3 - 4%
- 5 - 6%
- 7 - 8%
- 9 - 10%
- 11 - 12%
- 13 - 14%
- 15 - 16%
- 17 - 18%
- 19 - 20%
- 21 - 22%
- 23 - 24%
- 25 - 26%
- 27 - 28%
- 29 - 30%
- 31 - 32%
- 33 - 34%
- 35 - 36%
- 37 - 38%
- No Data
Figure 5. Same as in Fig. 3, except for the central–eastern mountain and Sonoran regime (CEMSR).
Figure 6. Same as in Fig. 3, except for the nondiurnal regime (NDR).
Figure 7. Ranked distribution by percentile of all 24-h precipitation totals (mm) from the ALERT network associated with CEMR (denoted by circles; N=3429), CEMSR (denoted by diamonds; N=1485), and NDR (denoted by X; N=2361). In 1997 (1999), the ALERT network contained 71 (96) stations.
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