Characteristics of Microbursts in Central Arizona

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ABSTRACT

Summertime thunderstorms in central Arizona associated with the North American Monsoon often become severe and are known to frequently produce damaging microbursts. Occurring in a rapidly growing metropolitan region, these costly and hazardous phenomena pose a critical challenge to forecasters and are of extreme concern to local power industries and airport operations.

In order to identify the spatial and temporal characteristics, evolution, and intensity of downbursts in central Arizona, data was utilized from a comprehensive radar network put in place to observe the 2008 convective season in the greater Phoenix area. An S-Band WSR-88D and C-Band TDWR were operational throughout the study, offering multiple views of the same storms. Using this new information, microbursts in central Arizona can be compared to previously documented microbursts from other regions, and evaluated in light of the current theoretical understanding of downbursts.

Microbursts in central Arizona observed during this study were all classifiable as either wet or high-reflectivity microbursts. They occurred most frequently between 5 and 9 PM MST (well after the time of maximum solar heating), and were associated with maximum low-level outflow velocity values either meeting or possibly exceeding those values previously documented. Further, they were observed to occur over scales ranging from 2 to over 20 km in diameter, and minutes to almost an hour in duration. Individual microbursts and line microburst formations occurred, and were seen by radar to exhibit characteristics closely matching, and thus supporting, the currently accepted conceptual models presented in the literature.

I. INTRODUCTION AND BACKGROUND

A. MONSOON THUNDERSTORM ENVIORNMENT

The southwestern United States and northwestern Mexico reside in the Sonoran Desert, which is greatly affected by the North American Monsoon system. The monsoon season is characterized by a mid-level wind shift from westerly to easterly, and a concentrated southerly or southwesterly transport of moisture at low levels from the Gulf of California onshore into the Sonoran Desert. The monsoon usually begins in early July and lasts until September, over which time the thunderstorm activity in this region is greatly enhanced. The North American Monsoon convective regime in central Arizona essentially only requires moisture advection interacting with strong sensible surface heating over complex terrain.

In the state of Arizona, isolated single cell thunderstorms are typically initiated in the afternoon along elevated terrain features, including the Colorado Plateau, Kaibab Plateau, Mogollon Rim, White Mountains, and Southeast Highlands. Elevation generally rises to the north and northeast, while the southwestern and central portions of the state remain in a valley with intermittent basin and range landforms. There is evidence supporting the development of microburst-producing-thunderstorms in regions of elevated terrain. For instance, Hjelmfelt et al., 1989 noted that, regarding microbursts in eastern Colorado, “strong surface heating is required to develop surface-based convection to break the cap… Therefore there is better convective potential for parcels on heated mountain slopes and elevated terrain.” It is commonly understood that a mountain-valley circulation consists of upslope flow occurs during the daytime as warm air parcels rise against the slopes and support cloud development toward the tops of the mountains. During the evening and nighttime, downslope flow begins where cooler air sinks back down the slopes of the terrain. Interestingly enough, Fujita 1981 illustrated that in the context of microburst development, “terrain induced flow could contribute to the formation of convective storms or morphology, i.e. downslope or drainage flow in the wake of a mountain”.

McCollum et al. 1995 did an extensive analysis of a summer time MCS in Arizona, which exhibited many common characteristics of the normal convective regime in this area. They noted that moisture advection into the foothills and mountain regions produced enough convective instability, moisture, and lift to support thunderstorm development. In the evening hours, the outflow of these thunderstorms moved downslope into the valley or lower desert as radiational cooling allowed for parcels to sink down the mountain slopes. An intensification of thunderstorms was then triggered by the interaction between northerly or northeasterly drainage flow, cool outflow boundaries from pre-existing convection, and southerly or southwesterly low-level monsoon moisture advection in a deep, unstable desert boundary layer. According to this model, thunderstorms often initiate in the afternoon hours along elevated terrain during the monsoon season in Arizona. In the evening hours or nighttime, they are known to intensify and become severe as they propagate southward, southwestward, or westward into the lower desert valley as the storm motion encounters opposing, unstable monsoon flow. The area of intensification happens to include many highly populated regions in central and southern Arizona, such as Phoenix.

B. MICROBURSTS

Severe thunderstorms in the central Arizona region, or in the Sonoran Desert, frequently produce microbursts during every monsoon season (Vasiloff and Howard, 2008). Microbursts in this region will henceforth be referred to as Sonoran microbursts. A microburst is a "strong downdraft that induces an outburst of damaging winds on or near the ground" (Fujita, 1981). It can be more informally described as a small area of rapidly descending air. When microbursts are accompanied by precipitation particles, the returns from such particles as seen by Doppler radar can provide many signatures with which to track their occurrence and monitor their evolution. For instance, Roberts and Wilson 1984 identified four prominent microburst radar signatures: upper-level convergence, mid-level rotation, descending precipitation core, and low-level divergence. This study focuses primarily on the very lowest level of the atmosphere as viewed by radar to analyze microbursts, so the low-level divergence signature was utilized exclusively for microburst identification purposes.

The low-level divergence wind pattern at or near the surface associated with a microburst is recognized on the base radial velocity scan by a strong radial couplet of strong inbound velocity in close proximity to an area of strong outbound velocity, where the center of the microburst is the transition between outbound and inbound moving particles, or the isodop. The center of the microburst is often co-located with a maximum in base reflectivity returns as well. This is thought to be because the microburst is born out of a precipitation loaded, collapsed thunderstorm updraft. In order to qualify as a microburst, the velocity differential, or algebraic difference between inbound and outbound velocities along a single radial across the microburst, must be at least 10 ms^{-1} (Wilson et al., 1984). Microbursts are also known to generate environments of strong low-level wind shear, which are extremely hazardous to aircraft. Additionally, strong near surface wind speeds on either side of the microburst outflow envelope can cause significant straight-line wind damage.

Microbursts come in a variety of morphological types. According to Wakimoto et al., (1985), if accompanied by heavy rain, they are known as wet microbursts. If accompanied by little to no rain, they are classified as dry microbursts. Additionally, microbursts can occur in a single or isolated fashion, associated with a single thunderstorm cell, in which they are considered individual microbursts. A line microburst is a family of individual microbursts interacting in close proximity to each other such that their outflow patters often merge to form either a discrete or homogenous linear axis of divergence, at least twice as long as it is wide (Hjelmfelt, 1988). Finally, a classification has been adopted in the past between microbursts which occur over diameter scales less than 4 km or more than 4 km, which are named microbursts or macrobursts, respectively. However, from the results from this analysis and in agreement with Hjelmfelt et al. 1989 and Rhinehart and Borho 1993, all phenomena are referred to as a microburst despite their length scale.

C. MOTIVATION

Sonoran microbursts cause significant damage in the central Arizona region, including heavy rain, tree damage, downed power lines or power poles, and structural damage mainly associated with strong near surface wind speeds and strong low-level wind shear. Quick changes in surface temperatures and a drastic reduction in visibility are also encountered during microburst onset, especially wet microburst onset. One of the strongest microbursts in Phoenix history occurred on 14 August 1996 with a 115 mph wind gust, setting a new Phoenix and Arizona state record. Unfortunately, this storm and its accompanying strong wind gusts and intense low-level wind shear caused over $160 million worth of damage. Sonoran microbursts obviously cause a significant socioeconomic impact to a variety of stakeholders in the greater Phoenix area. These stakeholders include those in the transportation industry, both on the ground and in the air, and to the entire spectrum of airport operations. Moreover, microbursts are of extreme concern to the power industry. A single downed power pole means power lost to thousands of customers and an abrupt temperature change associated with seemingly unpredictable thunderstorms causes tens of thousands of dollars lost in power generation. The statistics generated by Heinselman and Shultz 2005 are similarly astonishing, in which they found that the Phoenix Metroplex accounts for about 63% of the 5.1 million Arizona residents. Additionally, the Phoenix metropolitan area has seen an enormous population growth rate in the past couple of decade, a rise of about 43.5% between 1990 and 2000. All things considered, it can be inferred that not only are microbursts putting a densely populated, major metropolitan region at risk, the potential impacts of Sonoran microbursts in the Phoenix area are actually *increasing*.

Microbursts have historically posed a critical challenge to forecasters due to their extremely low-level, rapidly evolving nature. Even though Doppler radar is our best tool currently available to study and analyze these storms, there are significant limitations associated with using radar for prediction purposes. Inherently, radar systems suffer from a variety of limitations arising from their hardware constraints and specifications, but most importantly, microbursts are difficult to capture using radar because important features are often missed below the beam, between tilts vertically, or between scanning intervals temporally. It is hypothesized that less than 50% of straight-line wind events like microbursts are detected within the quantitative range of operational Doppler radars. Additionally, straight-line wind events are consistently rated as the hazard with the lowest forecasting skill score, as compared to rotational wind events (Atlas, 1990). In regard to Sonoran microbursts, the normal challenges associated with forecasting microbursts are enhanced by the presence of complex terrain, mountain-valley circulations, and monsoon forcings in the central Arizona region. Lastly, a detailed climatology of microbursts in central Arizona does not exist at this time to aid in the warning decision process. For all these reasons and more, Sonoran microbursts unequivocally deserve our attention as researchers and forecasters. Future studies will hopefully involve perspectives from both avenues of the science in order to reach results that are mutually beneficial and novel.

D. RESEARCH GOALS AND OBJECTIVES

To address the concerns raised by Sonoran microbursts, the first research objective of this study was to identify the spatial and temporal characteristics (or distribution), evolution, and intensity of microbursts in central Arizona. Secondly, Sonoran microbursts were compared to microbursts previously documented from other regions and to the current conceptual models. From these results, operational forecasting implications and the potential for forecasting improvements are then discussed.

II. DATA

It is important to note that in terms of rainfall amounts, the 2008 monsoon season was the 10th "wettest" monsoon season in Phoenix since 1896, according to the NWS/WFO in Phoenix. Therefore, this data set nearly represents the worst-case scenario for convective activity in this region, providing strong motivation for its analysis.

Data was collected from PHX, the Phoenix Sky Harbor Airport Terminal Doppler Weather Radar and KIWA, the National Weather Service Weather Surveillance Radar – 1988 Doppler. Complete specifications of each radar system can be viewed in Table 1.

NAME	**KIWA**	**PHX**
TYPE	WSR-88D	TDWR
ELEVATION AGL	427 m	332 m
SCAN TIME	5 min	1 min
PEAK POWER	750 KW	250 KW
WAVELENGTH	10 cm S-band	5 cm C-band
LOWEST TILT ANGLE	0.5°	0.6°
AZIMUTHAL RESOLUTION	0.5°	1°
RADIAL RESOLUTION	250 m	150 m

TABLE 1: RADAR SPECIFICATIONS

III. CHARACTERISTICS OF SONORAN DESERT MICROBURSTS

A. METHODOLOGY

From the PUFFS (Phoenix Urban Flash Flood Study, Vasiloff 2008) project radar archive, base scans of reflectivity (dBZ) and radial velocity (ms^{-1}) from the TDWR and WSR-88D were used exclusively for classifying microburst occurrence during the 2008 monsoon season. Over this time period, 14 days were identified during which microbursts occurred in the greater Phoenix area, as identified by KIWA, and damage reports were received to confirm damage made by storms. Since PHX was not operational until August, only 7 of those same days were also identified by the TDWR.

The goal of the author was to identify the characteristics of microbursts *while at peak intensity* to gain an understanding of what to expect from these storms in the seemingly worst-case scenario.

Using data from the lowest scans of each radar (0.5° tilt for KIWA and 0.6° tilt for PHX), microbursts were identified using the low-level divergence signature (Roberts and Wilson, 1984). Thus, microburst occurrence, or a microburst event, was classified as the time and place when the maximum inbound velocity was achieved as part of microburst divergence signature according to the base radial velocity scan. This value represents the peak low-level wind speed in the outflow branch of the microburst on the side closest to the radar. A minimum velocity differential threshold of 10 ms $^{-1}$ was used to distinguish microburst divergence.

We chose to define the "peak intensity" as when the maximum inbound velocity occurred for a variety of reasons. First, shear calculations documented in previous studies proved to be tedious, time consuming, and prone to error. Secondly, the measurement of shear itself is biased to a small diameter of interest, which does not fully encapsulate the full threat or sometimes-large extent over which these storms are seen to evolve. While low-level wind shear has historically been the main hazard of interest as far as microbursts are concerned, especially from the perspective of the aviation industry, low-level wind speeds are also very hazardous in this region. Moreover, strong near surface wind speeds as a result of Sonoran microburst development have identified to cause significant damage, such as downed power poles, trees, and structural damage, in the Phoenix metropolitan area. The choice to use the *inbound* velocity from the radar scans for our classifying purposes was due to the effects of attenuation by heavy precipitation cells at the center of the microbursts, especially when using the TDWR. Loss of energy along the beam through the center of the microburst distorts the outbound wind velocity measurements in terms of both the accuracy and the integrity of the visual representation of the storm as seen by radar imagery.

While at peak velocity, the microburst's approximate radius was measured, defined as the distance in km along a single radial from the center of the microburst, as identified by the transition zone of nearly zero velocity (isodop), to the location of the maximum inbound velocity. Additional measurements taken while at peak velocity include the maximum base reflectivity value of the storm cell associated with the peak divergence signature, time in UTC, location of the microburst center in latitude and longitude, and height above ground level of the microburst center as identified by the divergence signature along the beam of the radar where the values were obtained. An additional subjective interpretation of each microburst classified it as either occurring on the micro scale (diameter of outflow winds less than 4 km), or macro scale (diameter of outflow winds greater than 4 km). Moreover, each storm was morphologically identified as either an individual microburst or line microburst.

In cases where the occurrence of a microburst was unclear through radar interpretation, the case was thrown out. Also, only cases occurring below 1.1 km AGL were considered. This study was only focused on the lowest level of the microburst environment as identifiable by radar. In the event of either an individual or line microburst, the strongest pulse during the lifetime was used for classification purposes.

B. RESULTS

i. Spatial Characteristics or Distribution

Events occur all throughout central Arizona. 116 unique microbursts were classified by the WRS-88D. From those same storms, 43 microbursts were also identified by the TDWR. Storm motion was consistently from the north, northeast, or east, meaning that storms were almost always seen first by the WSR-88D and second by the TDWR. Storm motion was from the high terrain into the lower valley of the desert.

ii. Temporal Characteristics or Distribution

The average time of peak intensity was 7 PM MST or 02 Z. Microbursts generally reached maximum velocity anywhere between 5 and 9 PM MST or 00 to 04 Z. The fact that microbursts in this domain reach peak intensity in the evening is very intriguing because this is after the time of maximum solar heating, middle of the afternoon or 3-4 PM locally. Storms are normally thought to peak with the time of maximum solar heating due to the forcing provided through surface based convection. However, the complex terrain in the state of Arizona plays a unique role in the initiation and evolution of thunderstorms. For instance, thunderstorms are initiated in the elevated terrain during the afternoon due to the presence of an elevated heat source and upslope flow from the valley up the slopes of the mountains, together helping to overcome convective inhibition. During the evening, as incoming solar radiation declines, downslope flow from the north or northeast begins from the mountains into the lower desert, carrying convective activity into the Phoenix area. At this time, downslope flow interacts with the unstable monsoon boundary layer (characterized by an opposing low-level southerly or southwesterly flow) and cool outflow boundaries from pre-existing convection. The interaction of these forcing mechanisms between the mountain-valley circulations and monsoon environment is thought to trigger the intensification of storms during the evening hours in Phoenix. This is a clear example of how the complex terrain unique to the state of Arizona, and resulting mountain-valley circulations, is responsible for influencing microburst evolution and intensification in the Phoenix area.

iii. Evolution (radius; reflectivity; line and individual and asymmetry)

The average radius of Sonoran microbursts was 2.9 km, but ranged anywhere from 0.5 km to 12 km. We can conclude from these results that microbursts occur in a large variety of sizes in the central Arizona region. Additionally, not correlation was found between the radius and maximum inbound velocity, which means that a larger microburst is not necessarily stronger or weaker.

The divergence signature as seen on the lowest scan of the radar was always coincident with a maximum in reflectivity at the same level. The average base reflectivity value of microbursts while at maximum velocity was 56 dBZ, indicative of heavy rain on or near the ground. The maximum value recorded was 68.5 dBZ and the minimum was about 30 dBZ. 75% of microbursts exhibited base reflectivity values above 53 dBZ, 50% above 57 dBZ, and 25% above 60 dBZ. Through interpretation of these results, microbursts in the greater Phoenix area are unequivocally wet microbursts, occurring in concert with heavy rain and perhaps hail, graupel, or wet ice. This is counterintuitive because wet microbursts are thought not to occur in dry regions such as deserts. While Phoenix is certainly a desert region, it is a very unique desert. Through direct influence of the North American Monsoon system, the Sonoran Desert is characterized by a very deep, moist, unstable boundary layer conducive for deep convection. Again, this is a salient example of how the unique monsoon environment present in Arizona accounts for the extreme nature of microbursts in and around Phoenix. Finally, no correlation was found between reflectivity values and maximum inbound velocity, meaning that cells associated with higher precipitation were not necessarily stronger or weaker in terms of wind speed.

Both microburst lines and individual microbursts were identified. The typical evolution of an individual microburst could be seen on radar as the initiation of divergence at the surface following or coincident with an increase in the coverage and intensity of reflectivity on the accompanying lowest-level scan of the radar. After reaching peak intensity, cells either dissipated thereafter, pulsed several times before dissipating, or merged together with other individual microbursts to form long-lasting microburst lines. Individual microbursts most often led to the development of microburst lines. Lines hardly ever formed without prior development of, or the merging of, individual microbursts. Although many microburst cells and lines were symmetric, about an equal if not greater portion of storms were asymmetric, where outflow branches were skewed in one or more directions horizontally.

iv. Intensity

The maximum microburst base velocity value recorded was 41.5 ms^{-1}, or approximately 92.8 mph, and was associated with significant damage in Phoenix on 28 August 2008. The minimum peak velocity measured was 9.00 ms^{-1}, while 75% of cases exhibited peak velocities above 12.25 ms^{-1}, 50% above 16.75 ms^{-1}, and 25% above 22.00 ms^{-1}. The average peak microburst wind speed was 18.6 ms^{-1}. Microbursts often pulsed more than once after exhibiting their initial peak velocity. Interestingly enough, the pulses' peak velocity value rarely ever exceeded that of the initial pulse. Although very few cases (less than ten) exhibited maximum inbound velocities greater than the severe wind criteria (approximately 25 ms^{-1}), these storms should not be underestimated. This is a measurement of only one side of the microburst. It can be inferred that outbound velocity values approached or exceeded the inbound values, coupling to generate a very strong, low-level wind shear environment.

C. COMPARISON TO PREVIOUSLY DOCUMENTED MICROBURSTS AND CURRENT CONCEPTUAL MODELS

i. Differences

As demonstrated earlier, Sonoran microbursts reached peak intensity well after the time of maximum solar heating. While this is similar to the sea-breeze effect on Florida microbursts (Rhinehart and Borho, 1993), this is different from other microbursts documented in regions such as Colorado (Wilson et al., 1984), Oklahoma (Eilts and Doviak, 1987), or Utah (Milke and Carle, 1987). Microbursts that occur in these other regions peak approximately coincident with the time of maximum heating, as is normally the case with surface based convection. However, Sonoran microbursts peak later because of the mountain-valley circulations occurring in the domain due to the presence of complex terrain surrounding the Phoenix valley.

Sonoran microbursts exhibit higher base reflectivity values while at peak intensity than almost all other microbursts presented in the literature, with the exception of some cases in Colorado. However, the average base reflectivity value of microbursts in the central Arizona region surpasses the average values from Florida, Utah, and Oklahoma. Moreover, the average base reflectivity value of Sonoran microbursts exceeded even the maximum values exhibited by Florida microbursts. The heavier precipitation associated with microbursts in central Arizona is due most likely to the presence of an atypical monsoon boundary layer. Under this regime, ample low-level moisture content is advected northward from the Gulf of California. This is yet another example of how Arizona's unusual and complex mesoscale environment consistently leads to the development of strong, damaging microbursts in the central portion of the state.

Microbursts in central Arizona may have greater wind speeds than those previously documented from around the country, but is not possible to definitely make this statement because the author did not complete the same kind of analysis as those in previous studies. However, from the tables of values available in the literature, it is clear that Sonoran microburst peak wind speeds are as strong, if not stronger, than those from microbursts encountered in Florida, Colorado, Oklahoma, or Utah.

ii. Similarities

While using radar imagery to classify and observe microbursts in central Arizona, it was resoundingly clear that the evolution of these phenomena in this region as seen by radar fits the current conceptual models and microburst theories extremely well. The descending precipitation core, contact stage, spreading stage, and dissipation stage were clearly distinguishable. Additional pulses in microbursts formations were apparent with an increase in reflectivity at the lowest scan, followed by, or coincident with, an increase in low-level divergence. Individual microbursts and line microbursts were noted, with individual microbursts often merging together to form lines.

Similar to the findings in Hjelmfelt 1988, data from this study and observational analysis shows that microburst lines are both stronger and wider than individual microbursts. Using velocity values from both radars for microbursts occurring below 800 m, line formations as compared to individual microbursts exhibited a stronger average base velocity by 5.93 ms^{-1}, and occurred over longer average radius widths by 1.9 km.

Also in accordance to previous studies, no significant correlation was found between peak microburst low-level velocity and reflectivity or radius. Moreover, there was no evidence of a physical difference between microbursts occurring over diameter scales less than 4 km as opposed to diameters greater than 4 km. Therefore, in agreement with Hjelmfelt et al. 1989 and Rhinehart and Borho 1993, the distinction presented in the literature between macrobursts and microbursts is deemed arbitrary and irrelevant, having no representation to processes actually occurring in nature. This is supported by data from this analysis because microbursts ranged over all sizes and showed no trend in intensity with size. Nor did the visual representation of the microbursts during the radar analysis suggest that storms with diameters greater than or less than 4 km were characteristically different in any way. For these reasons, all storms in this study have been referred to simply as "microbursts", following the convention of both Hjelmfelt et al. 1989 and Rhinehart and Borho 1993.

IV. SUMMARY AND CONCLUSIONS

Microbursts occurring in Central Arizona are strong, unique, frequently occurring storms formed in a very atypical environment. Both the complex terrain and the North American Monsoon circulation interact with the formation, evolution, and intensification of these phenomena. Occurring every year in a densely populated region, federal and private sector industries and the public are directly affected by these microbursts, sometimes in a damaging, expensive, and dangerous manner. Due to their low-level, rapidly evolving nature, microbursts have and will most likely continue to be a critical challenge to forecasters. The current operational radar strategy, including both the TDWR and WSR-88D, is useful for detection purposes but is extremely limited for prediction purposes to produce enough lead time to issue an effective, accurate warning. However, the TDWR information could potentially be disseminated to airport personnel in a timely manner internally. To this end, advances are expected to be made with the upgrade of the national radar network to Dual-Polarized systems. This will hopefully aid in the warning decision process. The Phased Array Radar system would be ideal, considering its rapid, low-level scanning strategy. All things considered, the authors suggest that the most effective next step towards improved microburst forecasts and mitigation of damage to life and property would actually be to analyze the underlying atmospheric thermodynamic and dynamic environment rather than continue to focus on radar applications. Future work should focus on identifying the key thermodynamic and dynamic conditions conducive for monsoon thunderstorms to produce microbursts in this region. The null-case will also be explored, since currently there is not a clear understanding about why some thunderstorms produce microbursts and others do not. We feel that this analysis would be more effective than producing a radar-based detection or prediction algorithm. This is especially due to the fact that even though some parts of the detection process could potentially be automated, a subjective human perspective seasoned with situational awareness and experience in the field is necessary to accurately discern a microburst using radar imagery.

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1. NOAA NWS WFO Tucson, AZ Monsoon Statistics http://www.wrh.noaa.gov/twc/monsoon/monsoon_phx.php
2. NOAA NWS WFO Phoenix, AZ Arizona Weather History http://www.wrh.noaa.gov/psr/general/history/
3. Adams, D.K., and A.C. Comrie, 1997: The North American Monsoon. *Bull. Amer. Meteor. Soc.*, **78**, 2197–2213,
4. Atlas, David (Ed.). (1990). *Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference*. Boston, MA: American Meteorological Society.

5. Caracena, F., Holle, R. L., and Doswell, D. A., 2001: Microbursts: A Handbook for Visual Identification. http://cimms.ou.edu/~doswell/microbursts/Handbook.html
6. Doswell, C, III (Ed.). (2003). *Severe Convective Storms*. American Meteorological Society: Meteorological Monograph Series, Volume 28, number 50.
7. Eilts, M.D., and R.J. Doviak, 1987: Oklahoma Downbursts and Their Asymmetry. *J. Appl. Meteor.*, **26**, 69–78.
8. Elmore, K., J. McCarthy, W. Frost, and H. Chang, 1986: A High Resolution Spatial and Temporal Multiple Doppler Analysis of a Microburst and Its Application to Aircraft Flight Simulation. *J. Appl. Meteor.*, **25**, 1398–1425.
9. Fujita, T.T., 1981: The downburst: Microburst and Macroburst, Satellite and Mesometeorology Research Project, Research Pap. No. 210, University of Chicago, 122 pp.
10. Fujita, T.T., 1986: DFW microburst on August 2, 1985, Satellite and Mesometeorology Research Project, Research Pap. No. 217, University of Chicago, 150 pp.
11. Heinselman, P.L., and D.M. Schultz, 2006: Intraseasonal Variability of Summer Storms over Central Arizona during 1997 and 1999. *Wea. Forecasting*, **21**, 559–578.
12. Hjelmfelt, M.R., 1988: Structure and Life Cycle of Microburst Outflows Observed in Colorado. *J. Appl. Meteor.*, **27**, 900–927.
13. Hjelmfelt, M., R. Roberts, H. Orville, J. Chen, and F. Kopp, 1989: Observational and Numerical Study of a Microburst Line-Producing Storm. *J. Atmos. Sci.*, **46**, 2731–2744.
14. Maddox, R.A., D.M. McCollum, and K.W. Howard, 1995: Large-Scale Patterns Associated with Severe Summertime Thunderstorms over Central Arizona. *Wea. Forecasting*, **10**, 763–778.
15. McCollum, D.M., R.A. Maddox, and K.W. Howard, 1995: Case Study of a Severe Mesoscale Convective System in Central Arizona. *Wea. Forecasting*, **10**, 643–665.
16. Parsons, D.B., and R.A. Kropfli, 1990: Dynamics and Fine Structure of a Microburst. *J. Atmos. Sci.*, **47**, 1674–1692.
17. Raghavan, S (Ed.). (2003). *Radar Meteorology*. Kluwer Academic Publishers.
18. Rinehart, R.E., A. Borho, and C. Curtiss, 1995: Microburst Rotation: Simulations and Observations. *J. Appl. Meteor.*, **34**, 1267–1285.
19. Roberts, R.D., and J.W. Wilson, 1989: A Proposed Microburst Nowcasting Procedure Using Single-Doppler Radar. *J. Appl. Meteor.*, **28**, 285–303.
20. Tuttle, J.D., V. Bringi, H. Orville, and F. Kopp, 1989: Multiparameter Radar Study of a Microburst: Comparison with Model Results. *J. Atmos. Sci.*, **46**, 601–620.
21. Wakimoto, R.M., 1985: Forecasting Dry Microburst Activity over the High Plains. *Mon. Wea. Rev.*, **113**, 1131–1143.
22. Wallace, C.E., R.A. Maddox, and K.W. Howard, 1999: Summertime Convective Storm Environments in Central Arizona: Local Observations. *Wea. Forecasting*, **14**, 994–1006.
23. Wilson, J.W., R.D. Roberts, C. Kessinger, and J. McCarthy, 1984: Microburst Wind Structure and Evaluation of Doppler Radar for Airport Wind Shear Detection. *J. Appl. Meteor.*, **23**, 898–915.
24. Vasiloff, S.V., and K.W. Howard, 2009: Investigation of a Severe Downburst Storm near Phoenix, Arizona, as Seen by a Mobile Doppler Radar and the KIWA WSR-88D. *Wea. Forecasting*, **24**, 856–867.
25. Weather Decision Support System – Integrated Information (WDDS-II)
26. ArcGIS 9.2 Desktop: ArcMap