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UNUSUAL SEVERE WEATHER OUTBREAK OVER AND NEAR THE GREATER PHOENIX METROPOLITAN AREA ON 28-29 AUGUST 2008

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1. Introduction

Severe thunderstorms with damaging straight-line wind gusts frequently occur over the lower desert of south-central Arizona during July, August and early September, mainly during the evening hours. Maddox et al (1995) documented several large-scale weather patterns most frequently associated with severe summertime thunderstorm outbreaks over central Arizona, while Wallace et al (1999) examined summertime convective storm environments in order to discern differences between convective storm days (CSDs) and no storm days (NSDs) over the Greater Phoenix Metropolitan Area (GPMA).

The severe weather outbreak which commenced the evening of 28 August 2008 was particularly intense and long-lived, especially for the southwest United States. At least five waves, or bursts, of severe thunderstorms with damaging straight-line winds, large hail and locally heavy rain affected the GPMA and adjacent portions of south-central Arizona during a six-hour period beginning near 0230 UTC 29 August 2008 (730 pm MST 28 August). Anomalously strong mid-tropospheric winds, unusually large CAPE/instability and atmospheric moisture/precipitable water, proximity to an inverted trough, and passage of a weak upper level disturbance combined to set the stage for this high-impact event. Situational awareness regarding the potential for a severe weather outbreak was quite good, and valuable information was conveyed to WFO Phoenix and its customer base via the Storm Prediction Center (SPC), which initially issued a 'slight risk' for severe thunderstorms at 1630 UTC on 28 August (this product was updated/reissued during the afternoon and early evening), and by WFO Phoenix forecasters: hazardous weather outlooks (HWOs), area forecast discussions (AFDs), and e-mail/chatroom notifications to emergency managers and local media, issued from the evening of 27 August through late morning of 28 August, highlighted the unusual atmospheric conditions. However, confidence that a severe event would occur over the GPMA waned as the day progressed, and the local forecast issued at 2200 UTC 28 August, called for only a slight chance of thunderstorms during the upcoming evening (PoP, or probability of measurable precipitation, was lowered to 20%).

This severe convective event was likely the second-costliest to have occurred in the GPMA during the past 40 years (the 14 August 1996 storm, which resulted in $160M in damage claims across the north and northwest portions of the GPMA, remains the most expensive convective wind event since the early 1970s).

This paper will review the meteorological conditions preceding this event, briefly describe evolution of the event principally by NWS Doppler radar, and conclude by listing "lessons reinforced". This event possessed similar, though not identical, atmospheric precursors to other noteworthy severe convective events which affected the GPMA and adjacent portions of south-central Arizona on 16-17 August 2001 (Green, 2002) and 14 July 2002 (Green, 2003).

2. Synoptic Overview

'Breaks' (synoptic-scale decreases in cloud cover and precipitation) and 'bursts' (synoptic-scale increases in cloud cover and precipitation) in the summer monsoonal pattern are typically observed over the southwest United States, including southeast California and Arizona (Carleton, 1986). Indeed, a break in thunderstorm activity occurred over WFO Phoenix's area of forecast responsibility during the period 18-22 August as the subtropical ridge shifted south over the region. The ridge edged north of WFO Phoenix's area of forecast responsibility by 23 August; small, non-severe convective events occurred over portions of the GPMA on 23 and 24 August as marginal instability returned. However, significant increases in moisture and instability, coupled with stronger steering flow and increased vertical shear, would need to be in place before significant widespread convective events were possible.

Hurricane Julio passed over the southern end of the Gulf of California (GC) on 24 August 2008, then weakened and dissipated as it drifted north to the central GC. Frequently, passage of a strong tropical system over the southern end of the GC initiates a significant increase in low level moisture over southern and central Arizona, often in the form of a 'Gulf surge' (Rogers and Peterson, 2007; Brenner, 1974); indeed, low-level moist advection was pronounced across northwest Mexico and southern Arizona during the period 24-25 August 2008, as precipitable water increased to near 50 mm (2 inches), about 150% of the climatological norm, over the southern half of Arizona by 25 August. In addition to strong moist advection, Julio helped to strengthen the subtropical ridge to its north while lowering atmospheric pressure across northern Mexico. These changes resulted in development of a narrow ribbon of stronger-than-normal mid-tropospheric easterly winds across central New Mexico and Arizona. This weather pattern persisted for much of the week, and supported development of several periods of vigorous moist convection over southern and central Arizona. The first in a series of significant hydrometeorological events occurred over much of central and southern Arizona, as well as southeast California, the evening of 25-26 August (2 flash flood deaths were reported over western Arizona/southeast California), followed by a more localized flash flood event over the extreme eastern portion of the GPMA early the morning of 27 August (this event received widespread media exposure when a life-saving rescue of a motorist and her child was recorded by a helicopter pilot).

Convective potential over the south-central Arizona desert for a given calendar day during summer is predicated to some degree on the magnitude and areal extent of moist convection the previous afternoon/evening. The significant precipitation event of 25-26 August contributed to a rather benign/inactive evening on 26 August, as more stable thermodynamic conditions existed. By 27 August, WFO Phoenix and Storm Prediction Center (SPC) forecasters expected scattered convective storms to develop over portions of south-central Arizona during the afternoon and evening, given abundant moisture, more unstable conditions, and favorable steering flow from the northeast. The afternoon AFD, issued by WFO Phoenix at 2158 UTC on 27 August, began: "Looks like we are shaping up for another very active day". A SPC mesoscale discussion, issued at 2116 UTC 27 August (316 pm MST) for west-central and southern Arizona, indicated a WW (severe thunderstorm watch) was possible, since storm coverage was increasing along and south of the Mogollon Rim (higher terrain across central and east-central Arizona), and 1) MLCAPE of 1500-2500 m^2s^{-2} (J kg^{-1}) existed from the southwestern Mogollon Rim in central Arizona southward across the lower desert of southern Arizona, 2) effective bulk shear value was 15-18 m s^{-1} (30-35 knots) , 3) precipitable water was 44-51 mm (1.75-2 inches), and 4) northeast flow aloft would help steer storms from higher terrain over the lower desert. As such, PoP was elevated into the chance category over and west of the GPMA (30-40 %) for the evening hours, well above the climatological PoP of ~ 10%, with only a slight chance (20%) forecast for the evening of 28 August, since the atmosphere was expected to have stabilized somewhat due to expected overnight rainfall on the 27th. Interestingly, very little thunderstorm activity occurred over the Phoenix CWA during the evening of 27 August, although widespread moist convection occurred over southeast Arizona. The Phoenix WFO evening AFD noted "What once looked to be an active evening has not panned out for our forecast area. For Thursday (28 August) went ahead and made some adjustments to PoPs. During the period 1800-0000 UTC, really tried to accentuate PoP chances over elevated terrain

locations (east and southeast of Phoenix), since models indicate more significant positive vorticity will advect into Arizona from New Mexico. By evening, it looks like the cap (over the lower desert) will begin to erode, which will prime the valley for a *nice* (author's italics) convective event given CAPE up to 1500 m^2 s^{-2} (J kg^{-1}). Very strong northeasterly flow, on the order of 15 m s^{-1} (30 knots), will also be very helpful in advecting storms into our area. Therefore, have (increased) PoPs to account for this scenario."

During the late evening/night of 27-28 August, two narrow bands of non-severe convective storms propagated southwest, from southern Gila County (0600 UTC) to just south of Greater Phoenix [over northwest Pinal County] (0800 UTC) to southwest Yuma County (1000 UTC), as weak perturbations apparently interacted with the unstable environment. The WFO Phoenix mid-shift public forecaster, noting the nocturnal convection and overall flow pattern, called for isolated to scattered afternoon thunderstorm development over the Tonto National Forest northeast of Phoenix during the afternoon of 28 August, and stated "With an anomalously strong 500 hPa flow around 15 m s^{-1} (30 knots) between the ridge to the north and the persistent trough across northern Mexico, thunderstorm activity will likely propagate westward (over) the valley and desert floors late this afternoon and this evening." PoP was forecast at ~ 30% for the Phoenix Metro for the evening of 28 August.

Numerous convective storm parameters from the 0900 UTC 28 August 2008 SPC Short Range Ensemble Forecast (SREF) package (Bright et al, 2004) provided excellent guidance regarding the potential for a significant severe weather outbreak over south-central Arizona during the late afternoon/early evening of 28 August. For example, the Craven-Brooks Significant Severe (CBSS) parameter, which incorporates effective shear and MLCAPE, and the 'derecho parameter', which takes DCAPE and MLCAPE into account, targeted central and southwest Arizona as highly likely to experience a significant convective event during the late afternoon or early evening of 28 August 2008.

By the morning of 28 August, most observed convective parameters indicated potential existed for an unusually intense severe weather outbreak over southern Arizona during the upcoming evening. The 1200 UTC Phoenix special sounding, funded by SRP, possessed the following two key anomalous characteristics: 1) 15 m s^{-1} (30 knot) east-northeast wind at 500 hPa (climatological wind speed ~ 5 m s^{-1} (10 knot), which resulted in well-above-average vertical wind shear, and 2) MLCAPE > 800m^2 s^{-2} (J kg^{-1}), well-above the climatological norm of ~ 200 m^2 s^{-2} (J kg^{-1}). MLCAPE was anomalously large due to the combination of: 1) unusually high 1000-700 hPa mean mixing ratio of ~ 14.5 g kg^{-1} , and 2) a nearly dry adiabatic 700-500 hPa layer. A thunderstorm checklist designed by Jim Perfrement, a former senior forecaster at WFO Phoenix, indicated areal coverage for measurable precipitation during the upcoming evening over the Phoenix Metro would be > 50%, with a >30% chance for wind gusts over 50 mph (43 knots), and a > 30% chance for flash flood-producing storms: all values were the highest the checklist was designed to provide. In addition, a 1200 UTC sounding-based prediction model for Phoenix, Arizona forecasted a 95% chance for measurable rain during the upcoming evening (Rogers, 2009).

Upon receiving the morning briefing, the WFO Phoenix MIC composed and transmitted e-mail correspondence to a number of key customers, including emergency managers and media (TV, radio and print), informing them of the enhanced threat. The WFO Phoenix morning AFD, issued at 1637 UTC (937 am MST), highlighted the severe weather potential, but included the following caveat: "*The only potential pitfall with this scenario is the potential for drying over northern Arizona to limit the convection over the (Mogollon) Rim. Should few or no storms form upstream, we will have problems getting storms to form spontaneously over the lower central deserts, and our PoP (of 30% over Greater Phoenix) will end up overdone.*" This caveat referred to the fact that a very pronounced moisture discontinuity existed across central and eastern Arizona, with much drier conditions (surface dew points -5 to +3 deg C) along and north of the Mogollon Rim and White Mountains, while very moist conditions (surface dew points +15 to +20 deg C) existed to the south. The moisture boundary had become more prominent during the preceding 24 hours as dry advection occurred across northeast Arizona (situated east of an upper level high pressure area centered over southern Nevada), while southeast flow maintained anomalously high moisture over east-central and southeast Arizona (around an area of low pressure centered over far northwest

Mexico). Confluent flow between the upper high and the upper low resulted in anomalously strong mid-tropospheric east-northeast winds, especially across east-central Arizona and west-central New Mexico.

At 1660 UTC on 28 August 2008, SPC placed much of central and southern Arizona in a 'slight risk' area for the afternoon and evening of 28 August 2008. The outlook stated "Very moist low-level air continues to feed into southern Arizona with precipitable water remaining near two inches across the southwestern deserts. Lapse rates have increased across northern and western Arizona raising the concern for severe storms. In addition, 30 knot (15 m s^{-1}) east-northeast mid-level wind from the (Mogollon) Rim across the lower Colorado (River) valley supports efficient propagation of storms from the higher terrain in central Arizona into the desert valleys. Model soundings indicate DCAPE increases to about 1200 J kg^{-1} by mid-afternoon while MLCAPEs climb above 2000 J kg^{-1}. Strong/severe thunderstorms should develop quickly over the Rim and Bradshaw Mountains (north to northeast of Greater Phoenix) by early afternoon where full heating is now occurring. Forward-propagating convection should then move west-southwestward into desert valleys with potential for damaging winds and hail along with heavy rain given high precipitable water (values). With 30-35 (15-18 m s^{-1}) knots of deep layer shear, potential exists for one or more MCSs to develop across deserts enhancing the threat of damaging winds and heavy rain by later this afternoon/evening."

3. Event Evolution

During the late morning and early afternoon of 28 August, narrow convective bands propagated southwest across southern Arizona, well south of the Greater Phoenix area. As of 2100 UTC (2 pm MST), the Rapid Update Cycle (RUC) model initial conditions plot indicated the presence of a 30 knot (15 m s^{-1}) 500 hPa jet streak over eastern Gila County, which had propagated west from the vicinity of the White Mountains at 1800 UTC. However, even with the existence of this mid-tropospheric jet streak, little if any storm initiation had occurred over the higher terrain of central and east-central Arizona; rather, most activity was focused over the higher terrain of southeast Arizona, in the left exit region of this jet. The lack of convective development over the higher terrain north and east of Phoenix, especially by this time of day, suggested that upcoming evening/nighttime thunderstorm development over the lower desert of south-central Arizona would be limited, since fewer outflow boundaries would push southwest off the higher terrain toward Phoenix. Indeed, the mid-afternoon AFD from WFO Phoenix noted: "Well, it may turn out to be a bit less active (in terms of severe moist convection) than previously thought for this evening. Strong high to our northwest has set up a drying subsident northeasterly flow into northern/north-central Arizona, which has put a real 'kibosh' on the afternoon convection along the Rim. Satellite imagery showed minimal cumulus developing along the western/central Rim with just isolated storms starting to fire over the Eastern Rim (White Mountains). The 1800 UTC Phoenix raob indicated a mid-level cap had developed, along with a bit of mid-level drying. *Since dynamics are lacking we will probably need (outflow) boundaries to kick off significant storms.* Possibly (outflow) boundaries will move up later this evening from southeast Arizona where convective potential is high. Anyway, lowered PoPs this evening to chance (30%) south and east of Phoenix, with slight chance PoPs (20%) over and west of Phoenix."

By 2300 UTC (4 pm MST), a well-defined cluster of thunderstorms was affecting portions of Sonora Mexico, while storms over Arizona existed mainly southeast of a Tucson-to-White Mountains line. By 0000 UTC 29 August (5 pm MST 28 August), the RUC model 'initial conditions' plot indicated the 500 hPa jet streak had strengthened to 35 knots (18 m s^{-1}) as it propagated southwest, and was situated just east of the GPMA. Higher resolution output from the NAM-12 suggested that at least two jet maxima existed within the region identified as single jet maximum by the RUC. Thunderstorm activity over the south-central Arizona higher terrain was still rather meager: only a few thunderstorm cells had developed over southern Gila County well east of the GPMA. Most thunderstorm activity had developed in association with the inverted trough over the Texas Big Bend area and with the weaker trough over Sonora Mexico.

A SPC mesoscale discussion posted at 0052 UTC 29 August (552 pm MST 28 August) noted: "Potential for damaging winds appears to be increasing across parts of southern Arizona, which could require WW (weather watch)

issuance. Latest radar and visible imagery continues to reveal a slow increase in convective coverage across parts of southern Arizona, particularly across southeastern Arizona, where a loosely-organized cluster of strong storms is indicated. Evening Tucson and Phoenix raobs both reveal favorable thermodynamic environment for continuing storm development, and deep east- northeasterly flow above roughly 700 hPa would support west-southwestward storm propagation across the lower deserts. Should storms continue to increase across this area, potential for organized cold pool/outflow development could result in sufficiently widespread wind threat to warrant WW (severe thunderstorm watch) issuance." The 0100 UTC 29 August SPC convective outlook reiterated what was mentioned in the mesoscale discussion, but added "Westward-southwestward extent of survival of any such complex toward lower Colorado River appears uncertain because of stabilizing effects of earlier convection; however, visible imagery and trends in Gila Bend observation indicates some potential for well-mixed boundary layers just off northern rim of cloud canopy associated with thunderstorms over Sonora. Phoenix/Tucson 0000 UTC 29 August raobs indicate MLCAPE around 2000 J kg^{-1}, and favorable surface-based buoyancy should persist over lower elevations for another few hours".

Between 0000 and 0100 UTC 29 August (5 and 6 pm MST 28 August), an isolated severe thunderstorm affected a small portion of west-central Gila County about 110 km (68 miles) east of downtown Phoenix (this storm dissipated by 0115 UTC). Meanwhile, isolated non-severe thunderstorms began to develop near the White Mountains in east-central Arizona, about 200 km (125 miles) east-northeast of Phoenix; periodic thunderstorm initiation continued over and northeast of this location for several hours. Lower-middle tropospheric frontogenesis was occurring in and near the storm initiation region.

Between 0100 and 0200 UTC, the first wave of strong to severe thunderstorms to affect the lower desert of south-central Arizona propagated southwestward across central Pinal County (immediately south of Maricopa County, home to nearly all of the GPMA). The strongest storm exhibited classic severe storm characteristics as it affected mainly open country just south of Casa Grande, Arizona, a city 65 km (40 miles) southeast of the GPMA. Severe thunderstorm warnings were issued for this storm, mainly over western Pinal and southwest Maricopa Counties. This storm, as well as other storms to its south, produced modest cold pools with several distinct outflow boundaries detected by the KIWA WSR-88D, and the northern periphery of these outflows pushed toward the GPMA from the south. However, little if any convection occurred east and northeast of the GPMA, especially between 0115 and 0200 UTC. However, between 0200 and 0300 UTC (7 and 8 pm MST), isolated non-severe thunderstorms developed over and near the White Mountains in east-central Arizona, about 200 km (125 miles) east-northeast of the GPMA, propagated west-southwest across southern Gila County, then over eastern Maricopa County. Shortly after 0300 UTC, the small cluster of storms interacted with several intersecting outflow boundaries just east and north of the KIWA radar site; thus began the 'vicious cycle' of severe storm development that continued over and near the Phoenix Metropolitan area for the next 5 hours.

The second wave of severe thunderstorms to affect south-central Arizona, and the first to directly affect a portion of the GPMA, developed near the KIWA WSR-88D site in the far southeast portion of the GPMA shortly after 0300 UTC, then moved west-southwest across the far southeast Valley, adjacent portions of northwest Pinal County and southwest Maricopa County. Modest outflow from a distant severe thunderstorm over west-central Pinal County, part of the first wave of severe convective storms, pushed north toward the southeast Valley, and interacted with storms approaching the KIWA site, which led to very rapid thunderstorm intensification between 0300 and 0315 UTC. A damaging microburst, with peak winds likely in excess of 35 ms^{-1} (80 mph), occurred over and southwest of the KIWA WSR-88D, while peak outbound Doppler velocities in excess of 25 m s^{-1} (58 mph) in the lowest gate. A peak measured gust of ~ 35 m s^{-1} (77 mph) was recorded at the Chandler Airport at 0322 UTC.

By 0345 UTC, a third wave of strong to severe thunderstorms, more linearly oriented, which had developed over the higher terrain well east of Phoenix (southern Navajo and Apache Counties), was approaching the far East Valley. An outflow boundary generated by the Chandler Airport storm pushed north and collided with an outflow boundary generated from the third wave

of severe thunderstorms; explosive intensification of the third wave of storms occurred between 0415 and 0425 UTC, with development of a macroburst-producing MCS over the southeast Valley. This convective system intensified as it propagated west across Tempe and south-central Phoenix (Figure 1). Two distinct microbursts were embedded within the macroburst; the first developed just east of Sky Harbor International Airport just prior to 0430 UTC and reached peak intensity over/just west of the Airport (Figure 2); the second developed over central Phoenix, near Encanto Park, near 0500 UTC. According to damage reports and information gleaned from the KIWA and TPHX (Phoenix Sky Harbor Terminal Doppler Weather Radar), the most intense surface winds occurred over Tempe and south-central/central Phoenix between 0430 and 0515 UTC. A peak measured wind gust of 39 m s^{-1} (87 mph) was recorded by a meteorological wind sensor 1.6 km (1 mile) east of Sky Harbor airport at 0430 UTC, and Phoenix Sky Harbor ASOS recorded a peak wind gust of 33.4 m s^{-1} (75 mph) at 0438 UTC and a peak sustained wind of 24 m s^{-1} (55 mph) at 0440 UTC in association with the first microburst. A peak measured wind gust of 38 m s^{-1} (85 mph) occurred over central Phoenix at 0510 UTC in association with the second microburst. In addition to the destructive winds, locally heavy rainfall of 25-50 mm (1-2 inches) fell over the south-central portion of the GPMA between 0400 and 0530 UTC, resulting in urban flooding and localized flash flooding.

The fourth wave of severe thunderstorms to affect the GPMA intensified rapidly as it moved from higher terrain into far eastern Maricopa County after 0515 UTC, reached the far east portion of the GPMA by 0530 UTC, and produced intermittent severe weather between 0530 and 0600 UTC. This storm complex produced a macroburst, with peak sustained wind speeds in excess of 25 ms^{-1} (58 mph), hail as large as golf balls (4.4 cm, or 1.75 inch in diameter) and very heavy rainfall, especially over the northeast portion of the GPMA. Even though these storms were just as intense in terms of radar reflectivity as the third wave had been, peak outflow wind speeds were lower, primarily due to the fact these storms interacted with a less unstable boundary layer.

As was the case with the first through fourth waves of storms, the fifth and last wave of thunderstorms to affect the GPMA intensified as it moved west toward lower elevations. This area of storms affected primarily the north-central and northeast portions of the GPMA between 0630 and 0730 UTC (1130 pm 28 August to 1230 am 29 August). Winds in excess of 25 ms^{-1} (58 mph) and hail to 2.5 cm (1 inch) in diameter occurred with this relatively small area of severe thunderstorms. Both the fourth and fifth waves of severe storms affected the northeast portion of the GPMA; between 0530 and 0700 UTC, rainfall of 25-50 mm (1-2 inches) occurred over and near the communities of Carefree-Cave Creek-north Scottsdale-Fountain Hills, where localized flash flooding occurred.

Although the intense storms had moved west and south of the GPMA by 0730 UTC 29 August, thunderstorms continued to discretely propagate across southwest Arizona. A significant dust storm, driven by surface winds occasionally exceeding 26 ms^{-1} (58 mph) affected much of Yuma County, Arizona, and Imperial County, California between 0630 and 0830 UTC 29 August. The Yuma ASOS site, at the Marine Corps Air Station, recorded a peak gust of 25 ms^{-1} (57 mph) shortly after 0800 UTC.

WFO Phoenix issued 25 severe thunderstorm warnings, 3 flash flood warnings, 1 dust storm warning, and numerous severe weather and flood statements during this high-impact meteorological event.

4. High-resolution model results

The University of Arizona Department of Atmospheric Sciences performs operational high resolution WRF model runs over Arizona. Results from these runs will be presented, along with results from the new version of the WRF, version 3.1. During the summer of 2008, WRF v 3.0.1.1 was being used, and was configured to run using two domains with the inner domain at a resolution of 1.8 km. Model physics were configured using Lin et al 6 class cloud microphysics, the MYJ PBL scheme, Noah Land Surface Model, and the CAM radiation scheme. Two runs were produced each morning using that day's 12Z NAM and GFS NCEP models for the initial fields and lateral boundary conditions. Initial integrated precipitable water (IPW) fields were also corrected using data from GPS/IPW sensors.

The outbreak on the 28th was somewhat difficult to model as 12Z model initializations were in error with respect to initial location and coverage of precipitation and clouds. An area of showers and storms was ongoing at 12Z in southwest Arizona, and this convection was poorly initialized in both the GFS and NAM, though the GFS initial conditions were superior.

The band of convection across central Arizona produced only a few short lived strong storms, and had them displaced too far to the south (not shown). The model sounding for Phoenix showed significant CAPE and a very good shear profile, so the potential for organized severe storms was present.

WRF 3.1 was then used to rerun the GFS initialization from 28-29 August, with an applied update of the urban land surface data over Phoenix (derived from 2005 data, supplied by Susanne Grossman-Clarke of Arizona State University), as the original urban land use data was from 1991. The Lin microphysics was replaced with the new WRF Double Moment 6-class microphysics scheme. These changes improved the amounts and areal coverage of the precipitation across Maricopa County and the GPMA (Figure 3). Two waves of storms were produced by this run, similar to the multiple waves that actually moved through the Phoenix area. The WRF v3.1 also depicted the severe winds associated with these storms quite well.

Overall, the strength, coverage, and timing of the storms over Maricopa County were improved over the previous version and configuration of the WRF that was in operational use during summer 2008. However, the position of the convective bands was still shifted a little too far to the south. This new WFF configuration will be employed during the 2009 summer thunderstorm season.

5. Discussion and 'Lessons Reinforced'

At least five waves of thunderstorms affected east-central, south-central and southwest Arizona during the evening of 28-29 August 2008. The third wave of thunderstorms produced the most severe weather, mainly in the form of damaging wind: a large macroburst and at least two powerful microbursts were spawned as this MCS swept west across the central and eastern portion of the GPMA between 0400 and 0515 UTC 29 August. A storm initiation 'hot spot' was centered over and near the higher terrain (White Mountains) of east-central Arizona, about 125 miles east of Phoenix, where atypical low-middle tropospheric frontogenesis was focused. The frontogenetical forcing helped strengthen an anomalously strong core of mid-tropospheric winds across central Arizona (20-23 ms^{-1}), and shifted the core of strongest winds slightly north, which enhanced potential for severe convective storms over south-central and southwest Arizona, including the GPMA. Rapid storm intensification occurred as storms which initiated over the mountains moved over the lower desert and interacted with an extremely moist and unstable atmosphere. A number of convective parameters provided via the SPC-generated SREF, including MLCAPE, effective shear, Craven-Brooks significant severe (CBSS), and derecho, targeted south-central and southwest Arizona as highly likely to experience organized severe convective storms.

Forecaster confidence that an organized severe convective event would occur over and near the GPMA during the evening of 28-29 August 2008 was unusually high during the morning of 28 August, but decreased by that afternoon as storm development over the higher terrain (Mogollon Rim) northeast of the GPMA was much less than typically observed during the summer. Numerical models, including the NAM, GFS, and high-resolution WRF (University of Tucson) 'failed to convect' over the GPMA for this event. NAM and GFS-based MOS PoP for the ASOS site at Sky Harbor International Airport was in the mid-teens, only a few percent above the climatological norm.

This event occurred under very unusual atmospheric conditions for central and southern Arizona: moderate-high vertical wind shear (effective shear > 15.5 ms^{-1} (35 mph), moderate CAPE (> 2000 J kg^{-1}), well-above normal precipitable water (near 50 mm, ~ 170% of normal), and frontogenetical forcing. Forecasters underplayed the role frontogenetical forcing would play on the upcoming convective event, and overplayed the impact of dry advection from the north. Forecasters also placed too much emphasis on the relative lack of convective storm development over the Mogollon Rim during the early-mid afternoon hours.

Some lessons reinforced include: 1) A relative lack of moist convection over the Mogollon Rim

during the early to mid-afternoon is a *poor* indicator of what will transpire over the lower desert of south-central Arizona during the upcoming evening when strong vertical shear coincides with high instability over the lower desert (Green and Runyan, 2002). It is important to remember that most locally-developed rules and practices for forecasting convective outbreaks focus on moisture/instability rather than vertical wind shear, since wind fields over the southwest United States are typically weak during the summer convective season; 2) Though difficult, forecasters should strive to 'keep the faith' that an unusual meteorological event will occur in high shear/high instability situations. Even so, local expertise regarding expected or likely convective storm evolution under extremely unusual weather conditions may be lacking; it is precisely in situations such as these that SPC forecaster expertise is most-needed. nevertheless, a watch box was not issued prior to event onset).

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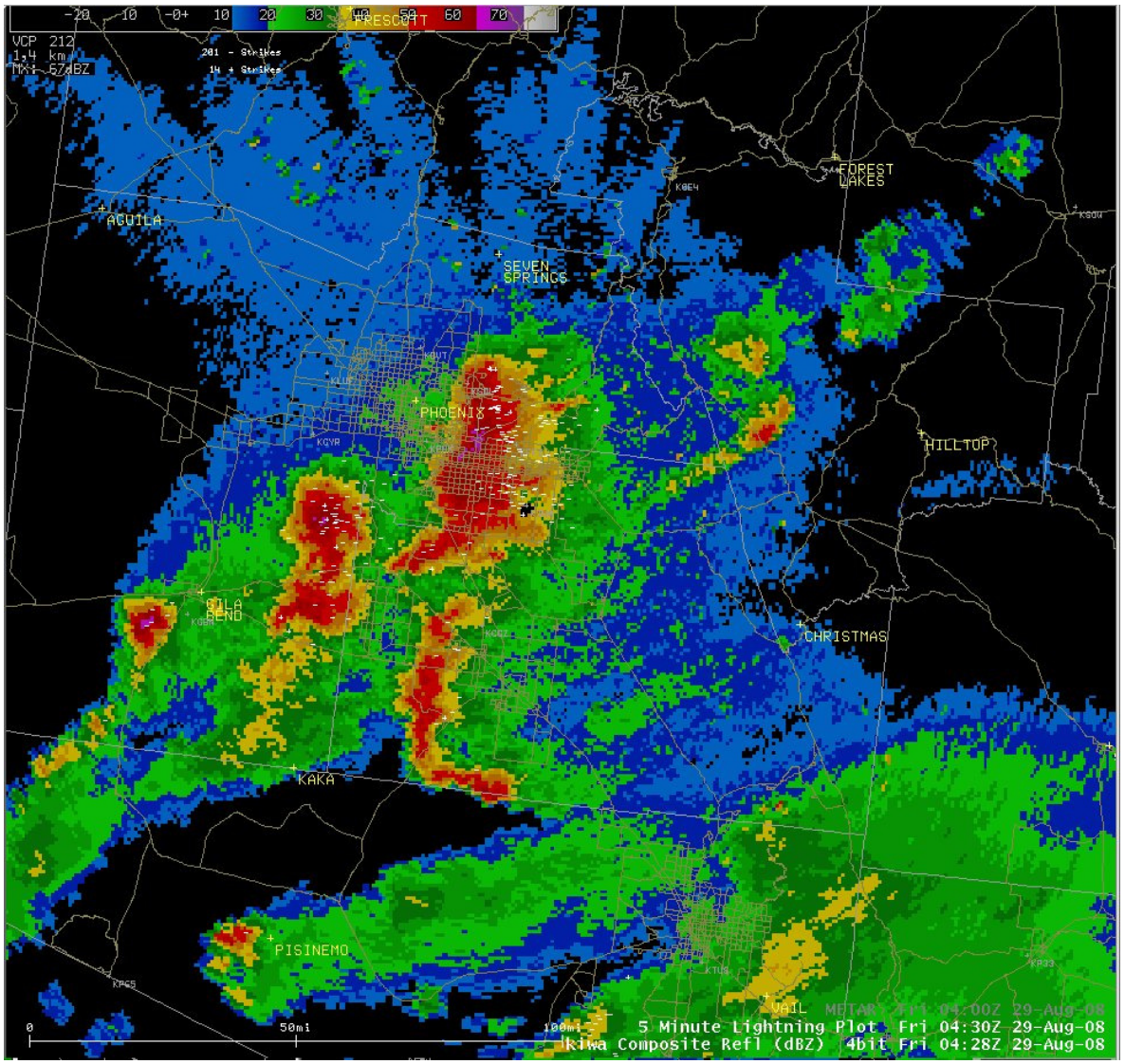

Fig. 1. KIWA composite reflectivity image at 0428 UTC. All five 'waves' of thunderstorms can be viewed, with the first wave of severe weather on left side of image. The third wave of storms was moving through central Phoenix at this time.

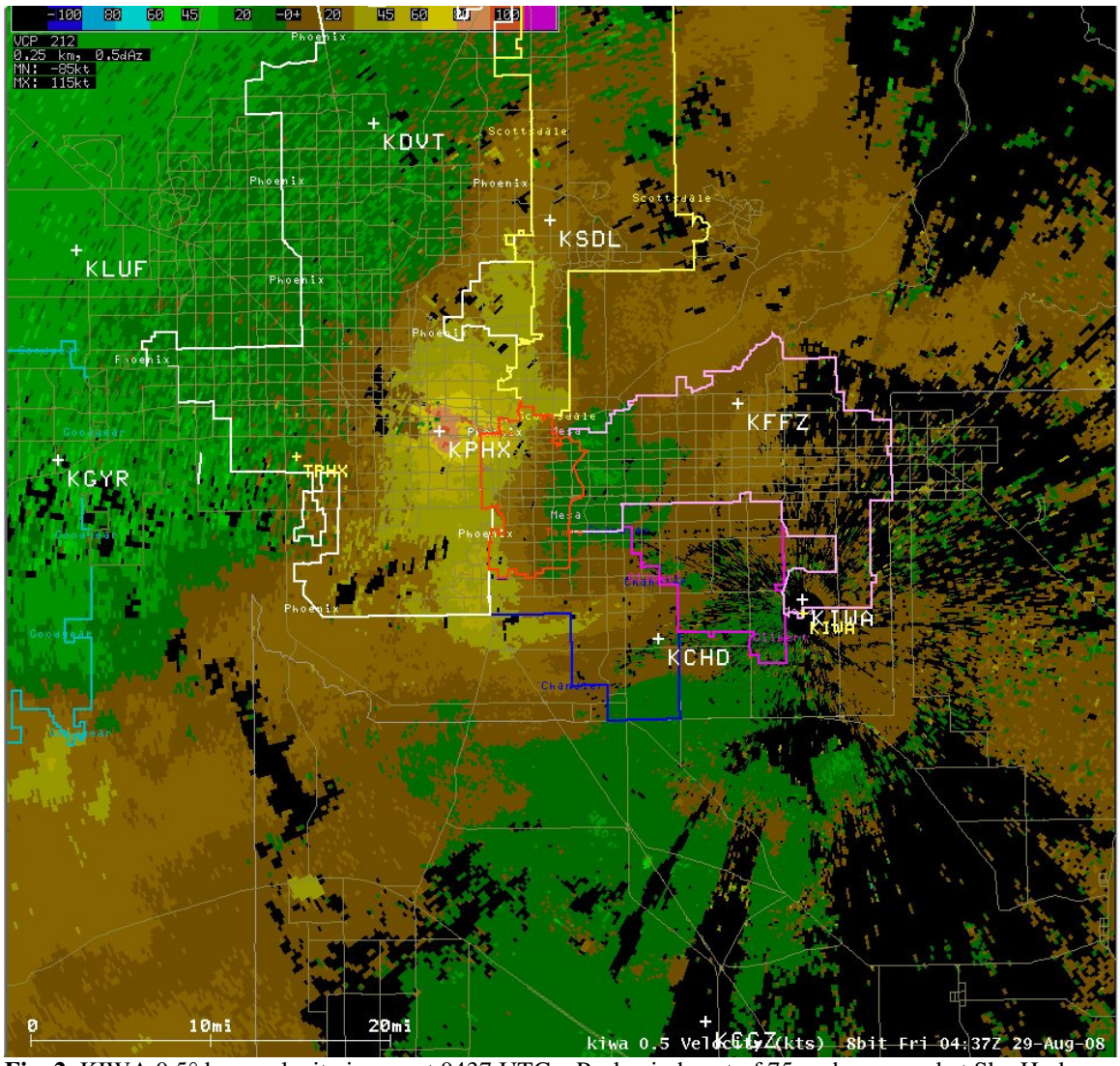

Fig. 2. KIWA 0.5° base velocity image at 0437 UTC. Peak wind gust of 75 mph occurred at Sky Harbor International Airport at this time.

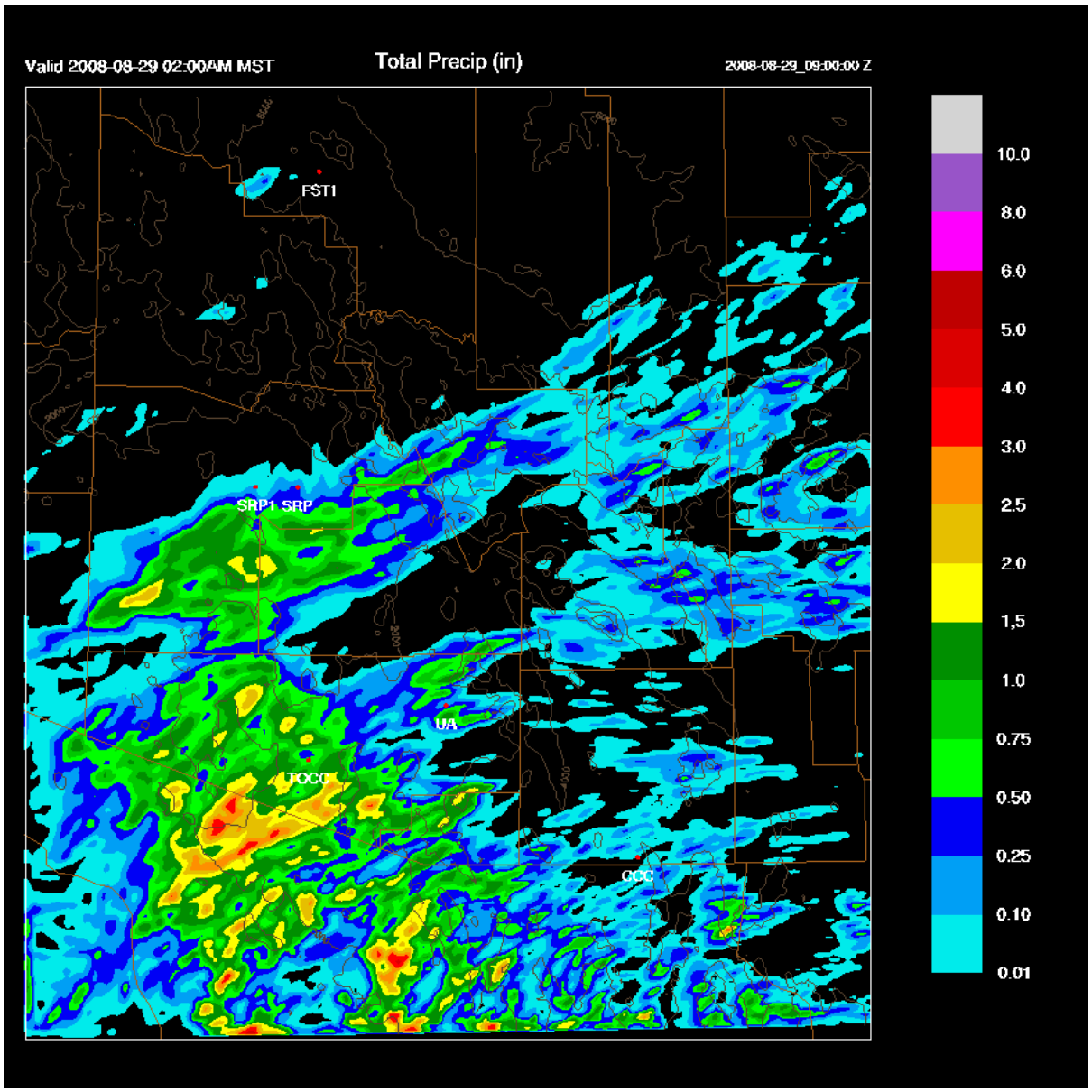

Fig. 3. WRF version 3.1 model forecast of total precipitation for August 28-29 2008. Operational WRF run depicted only light precipitation bands, positioned south of Phoenix.