P2.27 A SOUTH-CENTRAL ARIZONA HABOOB -- THE 28 JULY 1994 WIND AND DUST STORM. PART 2: RADAR AND SATELLITE OBSERVATIONS

Robert E. Wilt, Christopher A. Breckenridge, Jeffrey T. Davis, Michael W. Franjevic, William Wojcik, and Naeemah Cushmeer

NOAA/National Weather Service Forecast Office, Phoenix, Arizona

1. INTRODUCTION

A severe wind and dust storm, or haboob, affected much of the Greater Phoenix (Arizona) metropolitan area the evening of 28 July 1994. Haboobs typically *occur when strong thunderstorms southeast of Phoenix generate intense outflow winds that generate a wall of blowing dust. The dust may extend from the surface to 1.5 km AGL and typically moves with the leading edge of the gust front. In this case, visibility was reduced to near zero and southeast winds gusted to 50-65 knots over portions of Phoenix; at Sky Harbor International Airport, the visibility fell to one quarter mile while winds gusted to 42 knots. This was the first haboob to affect Phoenix since the KIWA WSR-88D, positioned at Williams Gateway Airport on the far southeast edge of the metropolitan area, became operational, the first to affect Phoenix since 5 June 1991, and the most intense in terms of wind and visibility since 1988.

The first of two papers on this 28 July 1994 severe event (Vasquez et al. 1997) focused on the usefulness of numerical model guidance, provided a synoptic overview, and reviewed the quality and accuracy of national and local products related to "event forecastability". This paper provides specifics regarding 1) event evolution based on satellite imagery, 2) thunderstorm development and evolution based primarily on radar data (supplemented by lightning data), and 3) accuracy and timeliness of short term outlooks, warnings, and follow-up statements issued by NWSFO Phoenix.

The authors provide several forecast "keys" that have proven to be quite useful with respect to determining the potential for severe convective storms to affect Phoenix and vicinity. As mentioned in the first paper, forecasting areal coverage and intensity of convective storms over south-central Arizona is particularly difficult during the summer convective season; dust storms, on the other hand, may occur even when no thunderstorms develop over the Greater Phoenix area, adding to the difficulty of the forecast.

2. EVENT EVOLUTION BASED ON SATELLITE IMAGERY

Hourly 6.7 micron water vapor images and 11.5 micron infrared images for the period 1200 UTC 27 July through 0900 UTC 29 July were reviewed in order to determine whether features not resolved by the standard upper air network or forecast by the numerical models may have played a role in the evolution of the severe event over Phoenix. In this case, with a strong anticyclone centered northwest of Phoenix, a deep layer of easterly winds existed across far southern Arizona and northern Mexico: given this scenario, disturbances in the easterlies typically propagate to the west and interact with thunderstorms which form daily over northwest Mexico.

On 27 July, morning water vapor and infrared imagery showed a well-defined vortex over northwest Mexico generated by a MCS which had developed the previous evening. This vortex, along with an arc-shaped band of moisture at and above 400 hPa, moved northwest into Arizona and southern California between 1500 UTC 27 July and 0300 UTC 28 July, and appears to have provided the moisture and dynamic support required to initiate deep convection from the Kaibab Plateau in northwest Arizona southeast along the Mogollon Rim in central Arizona to the White Mountains of eastern Arizona. Little thunderstorm activity was noted over southeast Arizona, although numerical and manual forecasts suggested this area would be most likely to experience deep moist convection. The lack of afternoon thunderstorms over southeast Arizona in this flow regime is typically indicative of unfavorable dynamics, since thunderstorms are nearly a daily occurrence over that portion of Arizona during the summer convective seson. As such, a lack of thunderstorms over southeast Arizona in this synoptic regime is usually indicative of the upcoming nighttime weather over south-central Arizona. Mid-level (600-400 hPa) winds were from the northeast, and storms began to propagate southwest toward Phoenix during the late afternoon and early evening, but were unable to redevelop over the lower desert of south-central Arizona due to relatively dry air in the well-mixed, 3.5 km deep boundary layer.

The second MCS in two nights developed over northern Sonora Mexico between 0000 and 1000 UTC 28 July, and began to dissipate by 1200 UTC. Moisture associated with the decaying MCS was evident over northern Mexico and southern Arizona between 1200 and 1600 UTC 28 July. Between 1800 and 2100 UTC, deep convection had developed along the Mogollon Rim and White Mountains, similar to what was observed the previous day. A cluster of thunderstorms developed over southeast Arizona and northern Mexico, which was markedly dissimilar to what had occurred on 27 July. Morning upper air data and numerical models indicated that an inverted trough present over far southwest New Mexico and northern Mexico may have provided the dynamic support for the southeast Arizona thunderstorms, but examination of water vapor imagery failed to reveal its presence (it is possible that the disturbance was more prominent below 400

**Corresponding author address*: Robert E. Wilt, National Weather Service, PAB 500, P.O. Box 52025, Phoenix, AZ 85072; e-mail: Bob.Wilt@noaa.gov

hPa, thereby making it difficult to detect via water vapor imagery; analysis of the upper air network data and model interrogation supports this hypothesis).

The interaction between storms propagating south and west off mountains north and east of Phoenix and the southeast Arizona thunderstorm cluster, which appeared to propagate toward the west and north, led to intersecting outflows and storm redevelopment over south-central Arizona. A key observation centered on the apparent northwest propagation of the southeast Arizona cluster: this unexpected propagation indicated that significant moistening had occurred in the sfc-850 hPa layer over south-central Arizona, which was confirmed by a rapid increase in Phoenix surface dew point from 14ºC to 19ºC between 1200 and 2100 UTC (this occurred in conjunction with a relatively light west-southwest surface wind, and was not forecast by any of the numerical models). Mostly sunny skies had been observed over south-central Arizona on 28 July, and the afternoon temperature had risen to 43°C (109°F) in Phoenix, 3 degrees above the climatological normal for the date. The combination of above-normal heat and moisture resulted in a ridge of theta-e air over south-central Arizona, and explains why storms propagated toward, and ultimately over, Phoenix.

By 2300 UTC, infrared imagery showed a cluster of new cells developing to the east of Phoenix between the line of storms north and east of Phoenix and the cluster of storms to the southeast of Phoenix. When thunderstorms northeast and southeast of Phoenix generate outflows that trigger storms east of Phoenix under deep east-northeast flow aloft, thunderstorms are likely to redevelop toward and over portions of the Greater Phoenix area. In this case, storms east and southeast of Phoenix became very intense, and generated strong, deep (3 km) outflow that moved rapidly toward the west-northwest. This outflow generated the dust storm that overspread the Phoenix area between 0100 and 0300 UTC, and triggered new thunderstorms over the Phoenix metropolitan area. This will be examined in detail in the radar section.

3. RADAR AND LIGHTNING OBSERVATIONS

This haboob was the first to occur over the Greater Phoenix area since the KIWA WSR-88D became operational in March 1993, and was the strongest in terms of wind and reduction in visibility due to blowing dust since 27 August 1988. KIWA is located at Williams Gateway Airport, 40 km east-southeast of downtown Phoenix. Although lowest elevation angle beam blockage exists to the northeast as well as due south of the radar, this location usually allows overall excellent interrogation of thunderstorm development. This was the first major severe weather outbreak to occur over Phoenix after the NSSL Warning Decision Support System (WDSS) became operational, and its output proved very useful during this event.

Between 1800 and 1900 UTC, thunderstorms began to develop over the Mogollon Rim and White Mountains, as well as over higher terrain south and east of Tucson. Cloud-to-ground lightning flashes statewide increased from 309 for the hour ending at 1800 UTC to 1745 for the hour ending at 1900 UTC.

By 1900 UTC 28 July, isolated strong thunderstorms were occurring over the Mogollon Rim northeast of Phoenix. Echo tops with a storm 140 km northeast of Phoenix had exceeded 15 km (50 kft) and VILs had exceeded 30; similar intensity was exhibited by a storm 160 km south-southeast of KIWA (south of Tucson). Forecasters, noting the unusual vertical development of storms so early in the day, became more confident that severe thunderstorms would affect much of southeast Arizona, with an improved chance that storms could propagate into south-central Arizona. NSSFC (now SPC), noting the unusually strong early convective development over the Rim and over southeast Arizona, issued a severe thunderstorm watch at 2025 UTC for much of southeast Arizona valid until 0300 UTC 29 July. The watch did not include the Phoenix metropolitan area.

Between 1900 and 2200 UTC, areal coverage of storms increased over the Mogollon Rim (elevation: 2.5 km MSL) and over southeast Arizona, and cloud-to-ground lightning flashes statewide increased from 3280 for the hour ending at 2000 UTC to 4053 for the hour ending at 2200 UTC. Wallace (1997) showed that Phoenix was likely to experience thunderstorms when statewide lightning flash rates of this magnitude were observed, especially when anomalously high lightning flash densities were observed 50-75 km east of Phoenix and steering flow was from the northeast in the 700-400 hPa layer. Time-height displays of reflectivity and radial velocity convergence/divergence with the strongest storms from the WDSS were not particularly impressive, although the first severe weather report (dime size hail) was reported with one storm 120 km northeast of Phoenix at 2200 UTC. Storms over the Rim began to propagate toward the southwest around 2200 UTC, while storms to the south and east of Phoenix continued to redevelop toward the north and west.

During the period 2230-2300 UTC, thunderstorms developed about 65 km east of Phoenix and became most intense in terms of vertical reflectivity and radial velocity convergence. These storms were triggered by outflow from an intense storm propagating off the Rim. The fact that these storms developed at 1.5 kft MSL indicated that stability had decreased at lower elevations due primarily to an increase in low level moisture (as compared to 27 July). By 2300 UTC, active thunderstorms were approaching Phoenix from the northeast, east, and southeast. The most intense storm propagating off the Rim was 100 km east-northeast of Phoenix and had an echo top of 15 km (50 kft), but a new storm was developing rapidly 80 km east-northeast of Phoenix. The most vertically reflective storms were 60 km east-southeast of Phoenix. Cloud-to-ground lightning flashes maximized at 4148 in the hour ending at 2300 UTC.

Between 2300 and 2340 UTC, 1) an arcing line of new thunderstorms developed from 140 km south-southeast of KIWA to 115 km east-southeast of KIWA along the leading edge of a northwestward moving outflow boundary generated by decaying storms over southeast Arizona; 2) the storm 80 km east-northeast of Phoenix intensified, with VIL reaching a peak of 45 kg m^{-2}, while the storm 100 km east-northeast of Phoenix collapsed, 3) an outflow boundary generated by the storm 80 km east-northeast of Phoenix moved southwest toward the vertically reflective storms 60 km east-southeast of Phoenix, and 4) a well-defined outflow boundary was propagating southwest from storms 70 km northeast of Phoenix. So, outflow boundaries were propagating toward Phoenix from the northeast and southeast, and strong thunderstorms continued to develop to the east and southeast of Phoenix.

Outflow intersection from the northeast and southeast occurred 50 km east-southeast of Phoenix around 2340 UTC. Severe thunderstorms, with mid-level radial convergence above 50 kt, echo tops to 16 km (53 kft), and VILs to 40, quickly developed at the intersection of the two outflows. These storms propagated west as the outflows continued to collide, then proceeded to generate strong to severe easterly outflow winds within 40 km of KIWA by 0040 UTC 29 July. The leading edge of this easterly outflow intersected outflow approaching Phoenix from the south, and new storms developed at the intersection point 18 km east-southeast of KIWA by 0110 UTC; at this time, strongest storms, with VILs 40-45, were 25 km northeast of KIWA. Cloud-to-ground flashes maximized with the new cells east-southeast of Phoenix between 2300 UTC 28 July and 0100 UTC 29 July, which was indicative of the location of the most vigorous updrafts and downdrafts during that time.

By 0130 UTC, the leading edge of a broad, deep (2.5 km) area of strong/severe outflow winds (large area of 36-50 kt winds, with small cores of 50-64 kt winds) and dust had reached the KIWA RDA site 25 km east-southeast of downtown Phoenix, so the severe wind and dust event (haboob) was well underway over the far east portion of Phoenix. The haboob proceeded to propagate WNW through the Phoenix metropolitan area between 0140 and 0300 UTC 29 July. The depth of the outflow was sufficient to initiate convection over much of the Phoenix metropolitan area, which aided and abetted the haboob, but these storms were much weaker than storms observed 1-2 hours earlier to the east of Phoenix.

Although the winds and blowing dust diminished as the haboob headed west, wind gusts to 35 kt and visibilities as low as 0.4 km were reported along the lower Colorado River between 0700 and 0800 UTC 29 July, so much of south-central and southwest Arizona ended up experiencing a period of blowing dust, very gusty winds and thunderstorms.

4. WARNING STATISTICS

From a warning standpoint, this situation was much easier to handle than the vast majority of severe events which occur over south-central Arizona during the summer convective season. The area affected by strong/damaging winds and blowing dust was quite large, and the KIWA WSR-88D allowed forecasters to provide very accurate statements indicating when and where severe weather would occur. Warning statistics for this event were: POD=0.7, FAR=0.333, CSI=0.583. The average lead time between issuance of a warning and severe weather occurrence was 27 minutes. All three warnings issued for Maricopa County (Phoenix is the county seat) verified, so, for Maricopa County, POD=1, FAR=0, and CSI=1!

5. CONCLUSIONS

A haboob, with 40-65 knot winds generating a wall of dust 2.5 km deep, affected the Phoenix metropolitan area the evening of 28 July 1994. The availability of high resolution radar, satellite and lightning data, as well as hourly surface observations, allowed Phoenix forecasters to issue timely, accurate special weather statements and warnings for this event, with a CSI near 0.6. This event showed how valuable WSR-88D radial velocity data could be to the warning forecaster.

Phoenix forecasters noted several items which have proceeded to aid in short-term forecasting of thunderstorms and duststorms over Phoenix. Specifically, the location, degree of areal coverage, and intensity of convective storms over higher terrain north, east and southeast of Phoenix is an important short-term (<6 hr) forecast tool. Duststorms are most likely to occur when a persistent area of thunderstorms generate strong winds over a dry landscape for a prolonged period, as was the case on 28 July. Lightning frequencies northeast, east, and southeast of Phoenix were well above what is typically observed on non convective days (Wallace 1997). The importance of thunderstorm outflow boundary intersection with respect to new thunderstorm development (Wilson and Mueller 1993), was clearly observed on many occasions during this event. Downdraft and outflow intensification was observed to occur 10-15 minutes after the observence of high values (> 40 kt) of radial convergece at and above cloud base (Roberts and Wilson 1989). Increasing surface dew points over south-central Arizona during daylight hours is an important clue regarding low-level moist advection, and increases the chances for thunderstorms.

6. REFERENCES

References will be available on request.