CENTRAL REGION TECHNICAL ATTACHMENT 97-01

The Southeast Nebraska Hailstorm of September 2, 1995

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1. INTRODUCTION

Nocturnal thunderstorms play an important role in the warm season distribution of precipitation across the central United States. They are also responsible for a significant amount of severe weather. These storms often organize into Mesoscale Convective Systems with damaging winds, hail and heavy rain.

Strong thunderstorms occurred in parts of western Nebraska during the late afternoon and early evening of September 1, 1995. However, these storms weakened shortly after sunset. Prior to examining parameters obtained between 0000 UTC and 0300 UTC, it appeared that eastern Nebraska would remain "capped" through the night.

During the late evening of September 1 and the early morning of September 2, 1995 a line of thunderstorms moved east through southeastern Nebraska. An elevated supercell developed slightly west of the main convective line, and produced a swath of enormous hail as it moved southeast. Enormous hail is greater than 2 inches (51 mm) in diameter, and occurs approximately 178 times annually in the continental United States (Schaefer et al. 1985). The purpose of this paper is to examine the dynamic and thermodynamic state of the troposphere that led to the formation of the southeast Nebraska hailstorm of September 2, 1995.

The initiation of nocturnal elevated convection is one of the most difficult events to forecast. Elevated thunderstorms are those that occur above a frontal surface. Such storms are isolated from surface diabatic effects (Coleman 1990). Upper air soundings, which are only received twice a day, are often not representative of the actual storm environment. Hourly surface observations can be misleading, since these storms typically develop near the top of or above the boundary layer, in association with the low level jet.

To accurately predict elevated thunderstorms, operational forecasters need to visualize the dynamic and thermodynamic state of the troposphere three-dimensionally. Diagnosing the possibility of thunderstorm development from a careful analysis of rawinsonde observations is crucial. Currently, forecast soundings can be automatically created for points between upper air reporting stations using the latest model gridded output. This was not the case at the Omaha office in September 1995.

This case is significant for three reasons. First, it is the only reported occurrence of 4 inches or greater diameter hail in Lancaster county Nebraska since the **Storm Data** publication started in 1955. Secondly, this event did not occur during the climatologically favored time of day (late afternoon and early evening). Finally, this case did not occur during the normally favored time of year (April-July) as discussed in the paper by Schaefer et al. (1985).

2. SYNOPTIC ENVIRONMENT AT 0000 UTC

Early in the evening of September 1, 1995, an area of surface high pressure was centered along the Wisconsin/Illinois border. A nearly stationary front extended from southwest Kansas into western South Dakota (Figure 1). Surface dew points were between 65°F and 69°F (18°C to 20°C) from Norfolk to Grand Island and North Platte, but only near 60°F along the Iowa/Nebraska border.

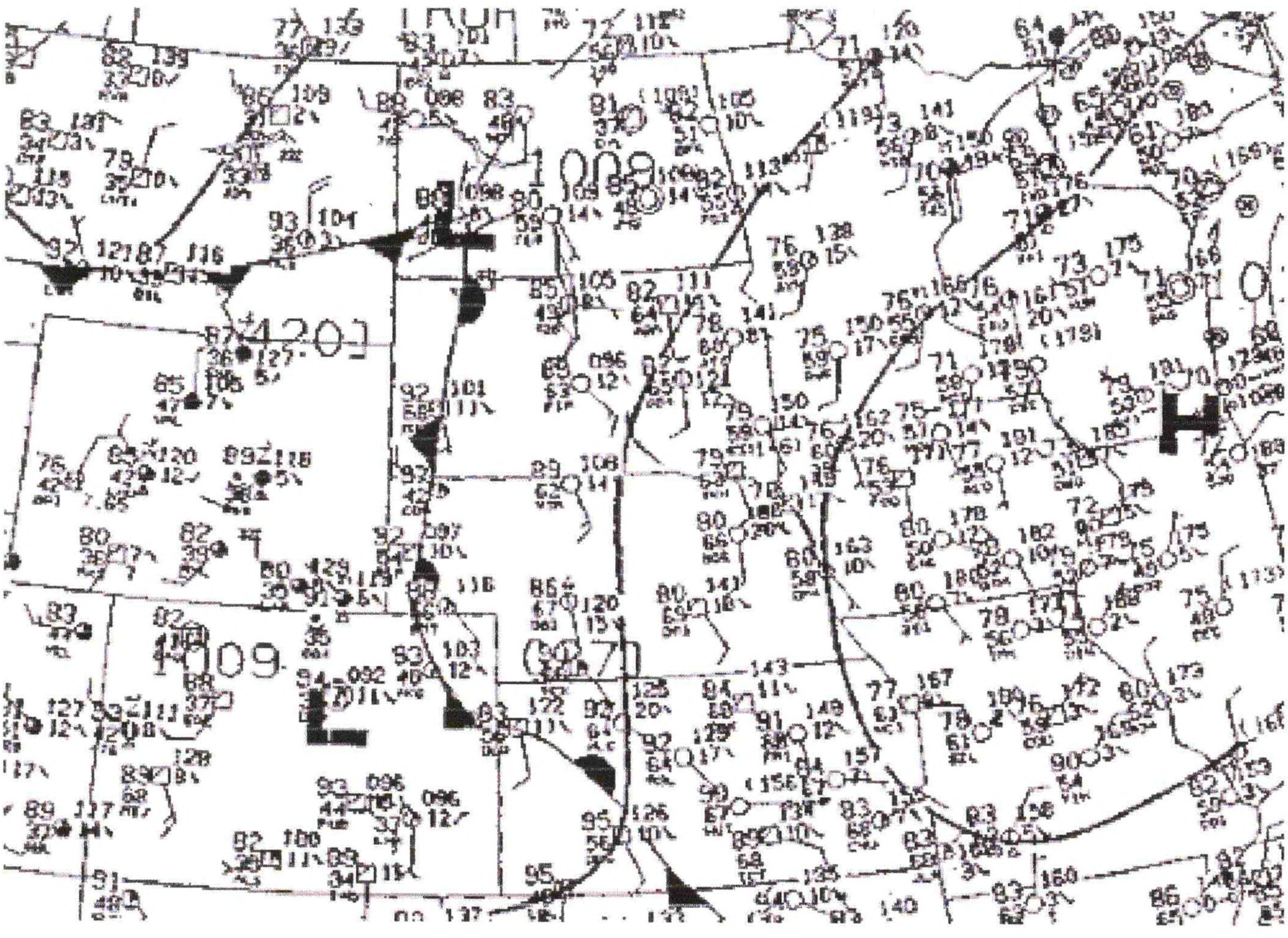

Figure 1. 0000 UTC Saturday 2 September 1995 NMC Surface Analysis. *Note* that the thunderstorms developed east of the stationary front.

A south wind of 10 to 15 knots (5.2 to 7.7 m/s) was over central and eastern Nebraska at 850 hPa. The main parameter noted at this level was a ribbon of relatively high moisture in the Central Plains. The ETA model 850 hPa height and dew point analysis using the National Weather Service (NWS) PC-based GRidded Information Display and Diagnostic System (PC-GRIDDS) indicated an axis of dew points greater than or equal to 14°C extending from eastern Oklahoma to south central South Dakota.

A weak shortwave trough was discernible at 700 hPa from western Minnesota to northeast Colorado. This feature was moving southeast and was also evident in the 500 hPa analysis (Figure 2). A speed maximum in the polar jet at 200 hPa was located from the Dakotas into southern

Minnesota. The jet streak would translate southeastward during the night, placing eastern Nebraska in the right entrance region after 0600 UTC. The latter are typically a favored area for mid tropospheric upward vertical motion associated with the direct circulation induced by the jet streak. However, the model output valid at 0600 and 1200 UTC showed only a weak ageostrophic circulation over southeast Nebraska.

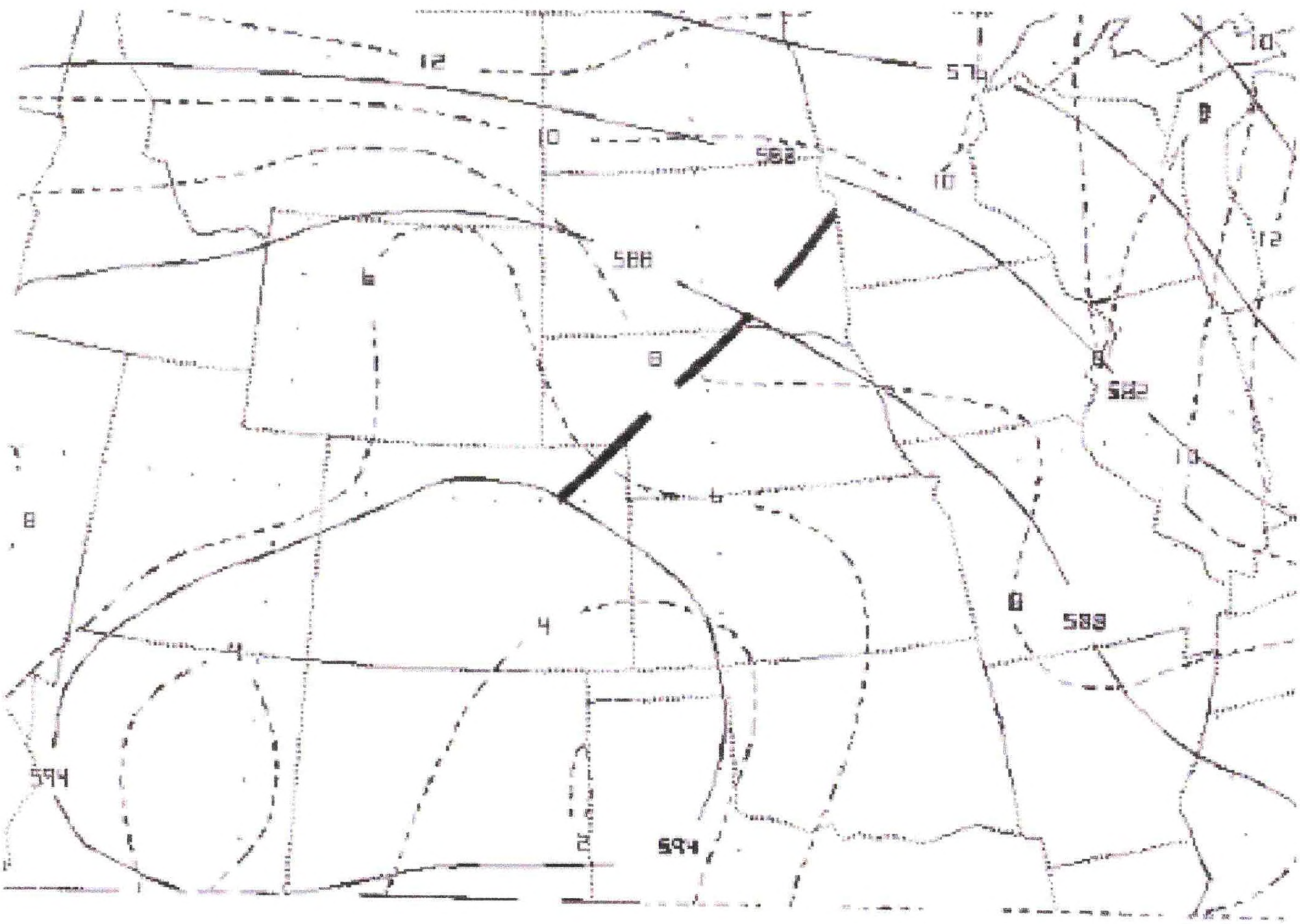

Figure 2. 0000 UTC Saturday 2 September 1995 ETA model 500 hPa height and vorticity analysis using PC-GRIDDS. Heights indicated by the solid lines (dm), absolute vorticity ($10^{-5}S^{-1}$) - dashed, and shortwave trough axis - heavy dashed.

The 850 hPa to 700 hPa layer mean Q-Vector convergence at 0000 UTC (Figure 3) showed a maximum near the Nebraska/Kansas border southwest of Hastings. Although not quite as strong, an area of convergence was also evident in the 6 hour forecast valid at 0600 UTC (figure not shown). Isentropic lift was shown on the 312 Kelvin (K) isentropic surface (Figure 4). Note that the pressure in the storm development area was between 800 hPa and 750 hPa on this isentropic surface. Fairly significant advection of equivalent potential temperature (θ_e) was noted at both 850 hPa and 700 hPa over eastern Nebraska.

Parameters from the North Platte, NE (LBF) and Valley, NE (OAX) 0000 UTC soundings obtained using the Skew T/Hodograph Analysis and Research Program (SHARP) Workstation (Hart and Korotky 1991) are summarized in Table 1.

Figure 3. 0000 UTC Saturday 2 September 1995 ETA model Q-Vectors and divergence of Q (10^{-19}m $Pa^{-1}m^{-2}s^{-1}$) initialization. The Q-Vectors and divergence are a layer mean from the 850 hPa to 700 hPa levels. The area of strongest convergence was over south central and southwestern Nebraska.

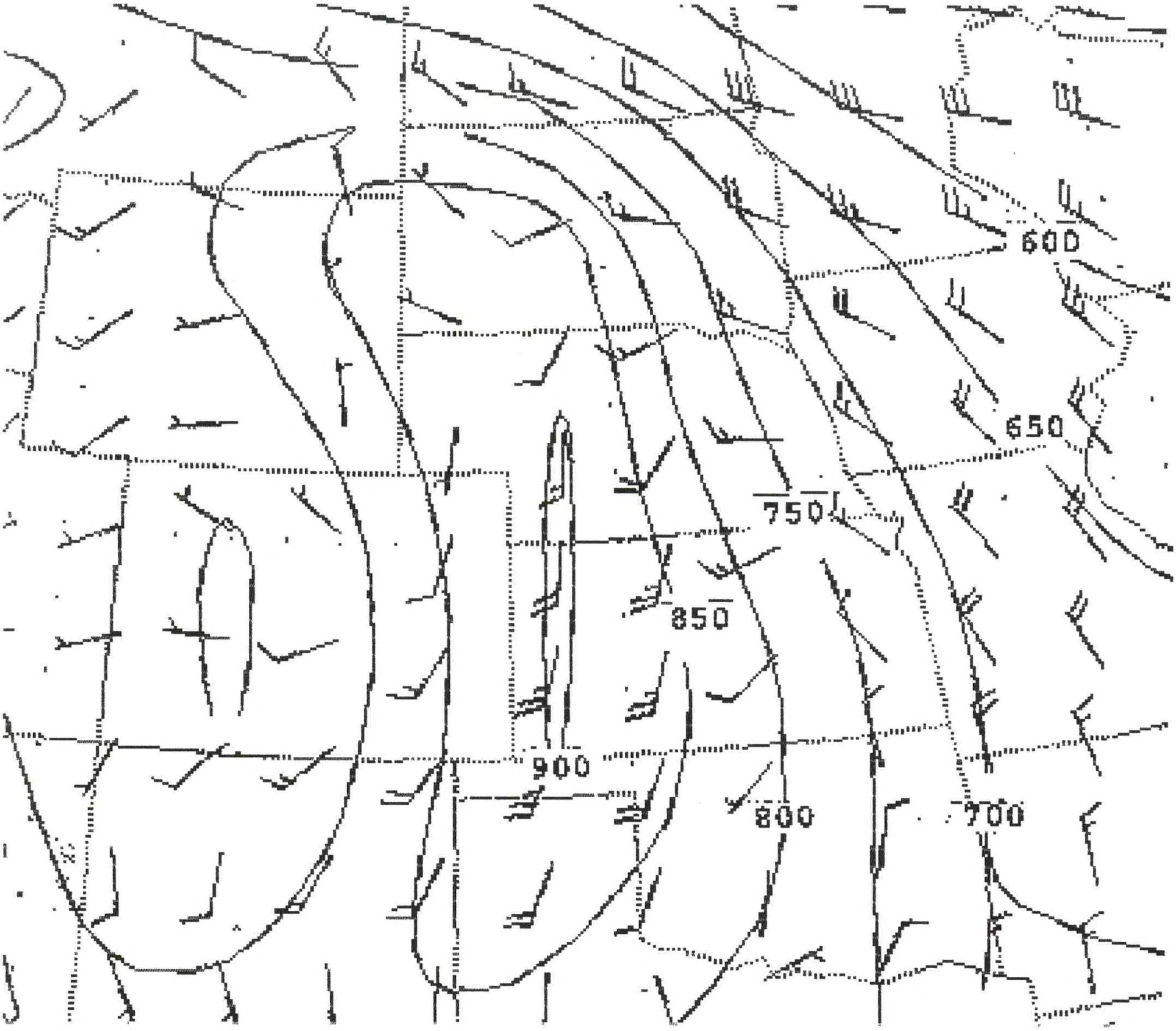

Figure 4. 0000 UTC Saturday 2 September 1995 ETA model 6 hour forecast of the 312 K isentropic surface valid at 0600 UTC. Solid lines are pressure (hPa) and barbs are in kts. *Note* that the storm development occurred in the area between the 800 hPa and 750 hPa levels.

Table 1
These parameters were obtained from the 0000 UTC September 2, 1995 rawinsonde observations from North Platte, NE and Valley, NE.

Parameter	North Platte	Valley
CAPE (surface based)	2920 J/kg	88 J/kg
Lifted Index	-8	0
K Index	30	9
BRN	44	1
Tropopause	50,100 ft	42,800 ft
Precipitable Water	1.32 in	0.91 in
Wet Bulb Zero height	10,800 ft	9,700 ft
SREH (0-3 km)	317 $(m/s)^2$	52 (m/s)

3. MESOSCALE STORM ENVIRONMENT

To assess the potential for deep moist convection, we must first examine the forecasted strength and distribution of large scale instability (Johns and Doswell 1992). Conditions were very unstable (lifted indices of -6°C to -9°C) over western Nebraska at 0000 UTC. Strong surface heating across this area contributed to the formation of scattered thunderstorms, which continued into the evening hours. The atmosphere was more stable in eastern Nebraska, and there was a strong cap (relative to surface based convection). However, the Valley, NE (OAX) and North Platte (LBF) soundings did not accurately depict the atmospheric conditions in the area where low level moisture was at a maximum. Table 2 represents the parameters in the storm development area at 0600 UTC.

Table 2
These parameters show indices derived from the proximity sounding near the thunderstorm development area.

Parameter	Estimated Storm Environment sounding
CAPE (lifted from 800 hPa)	2343 J/kg
Lifted Index	-6
K Index	38
BRN	45
Tropopause	48,000 ft
Precipitable Water	1.56 in
Wet Bulb Zero height	10,102 ft
SREH (0-3 km)	308 $(m/s)^2$

The proximity sounding was obtained by modifying the 0000 UTC OAX upper air data using the SHARP workstation. Temperature and moisture values were obtained from the ETA model gridded output. Wind information was obtained from a combination of the ETA model and the OAX WSR-88D VAD wind profile. The modified sounding resembles the Type I sounding discussed by Miller (1972). Although large hail did not appear likely with this sounding (because of the relatively high wet bulb zero height), the convective available potential energy (CAPE) and storm relative environmental helicity (SREH) was impressive. The CAPE suggested that a maximum vertical velocity of 65 to 70 m/s was possible (Bluestein 1993). The cloud base assumed from the lifting condensation level (LCL) was 6747 ft above ground level (AGL).

Moisture in the surface to 850 hPa layer continued to be transported into the southeast one-fourth of Nebraska during the evening, especially after sunset as the low level jet strengthened. An ETA model cross section (forecast) of θ_e and relative humidity, valid at 0600 UTC, was taken from North Platte to Omaha (not shown). An area of greater than 60 percent relative humidity was predicted to be near the storm development at approximately 5000 feet AGL.

From the cross section it could be seen that θ_e decreased with height, which implies convective (potential) instability (Bluestein 1993). This would only be true for a saturated atmosphere. The greatest difference in θ_e between 850 hPa and 500 hPa at 0000 UTC (figure not shown) was over western Nebraska. This axis would move approximately 160 km east by 0600 UTC.

Although only weak mid-tropospheric vertical motion was forecast ahead of the shortwave trough, the upward motion caused layer destabilization. According to the proximity sounding, the 700 hPa to 500 hPa layer lapse rate decreased to 7.5°C/km as potential instability was realized.

The SREH in the zero to three kilometer (0-3 km) layer suggested that supercell thunderstorms could develop. Values of 0-3 km SREH between 300 and 449 $(m/s)^2$ indicate potential for strong mesocyclones and tornadoes (Davies-Jones et al. 1990). However, a tornado did not develop here, as is typical with elevated thunderstorms. In a study by Grant (1995) tornadoes accounted for only around 1 percent of severe weather reports associated with elevated thunderstorms. The reader is cautioned however those dynamic pressure gradients generated in supercell thunderstorms can lift negatively buoyant air, and that tornadoes can occur occasionally. The depth of the inversion seems to play a key role in tornado development.

Strong Q-Vector convergence, advection of low level moisture and isentropic lift seems to have been the largest contributor to the initial thunderstorm development in eastern Nebraska. Frontogenetical forcing and the ageostrophic circulation associated with the jet streak were weak, and did not appear to significantly add to the destabilization process.

4. STORM CHARACTERISTICS AND DOPPLER RADAR OBSERVATIONS

Multicell thunderstorms initially formed 35 nm (65 km) west of Columbus, NE between 0330 and 0345 UTC near the 700 hPa θ_e axis. This was also near the area where the 0000 UTC ETA model initialization showed the maximum horizontal positive θ_e advection at 700 hPa.

During the first 20 to 30 minutes the reflectivity pattern had somewhat of an "odd" appearance (i.e., not what would normally be expected with severe local thunderstorms). The radar returns were oriented in a narrow and short north to south line. The precipitation developed from a band of Altocumulus Castellanus type cloudiness. This development was evident with infrared (IR) satellite imagery.

At 0402 UTC the highest reflectivity at 0.5 degrees as determined by the WSR-88D radar at Valley, NE (KOAX) within the system was 61 dBZ. Golfball size (1.75 inch) hail fell in Merrick County at 0420 UTC and 0.75 inch hail occurred in Polk County at 0505 UTC. These reports were outside the NWSFO Omaha county warning area. The system expanded in coverage and by 0533 UTC resembled a short squall line.

The first severe local storm report in the NWSFO Omaha county warning area was documented at 0530 UTC in Butler County, three miles north of Ulysses. One inch diameter hail occurred at that location. This was associated with a maximum reflectivity of 66 dBZ and a VIL (Vertically Integrated Liquid) of 63 kg/m^2. The estimated VIL of the day (VIL that would produce 0.75 inch hail) was 55 to 60 kg/m^2 (obtained using methods derived from a local office study). Since the cloud base with the storms in Merrick and Butler counties was probably near 6700 ft (2.0 km) and the storm was "elevated", it is suspected that not much of the 0-3 km SREH was utilized by these "pulse" type storms.

Around 0530 UTC an outflow boundary from the Butler county thunderstorm moved west, away from the squall line. As stated previously, this was in an area of isentropic lift with parcels rising from southwest to northeast. Convergence and lift were enhanced along the outflow boundary and a new cell developed slightly west of the main line of storms. This cell formed in a more moist environment and the cloud base was probably near 4000 ft (1.2 km) AGL. Since the cloud base associated with this storm was lower than the initial squall line, it is possible that the new storm was more able to effectively utilize the available 0-3 km SREH because the cloud inflow layer was deeper (closer to the earth's surface). A mesocyclone developed shortly after this storm formed. The circulation could be seen in the 0539 UTC Storm Relative Velocity Map (SRM) from the OAX WSR-88D over eastern Polk County (Figure 5). The height of the center of the radar beam at this location was 5300 ft AGL.

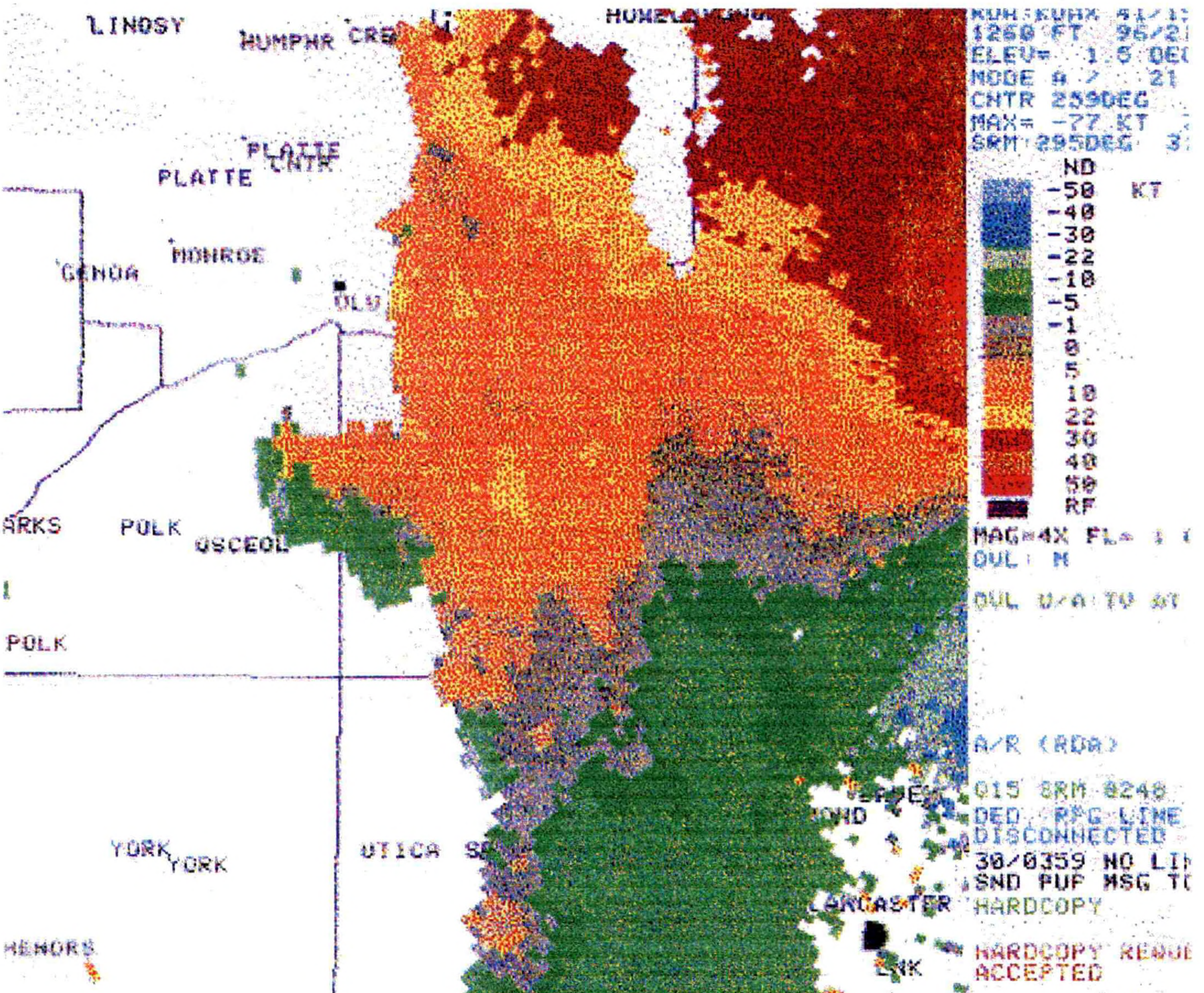

Figure 5. 0539 UTC September 2 1995 Storm Relative Velocity Map (SRM) from the KOAX WSR-88D. *Note* that the circulation is displaced west of the main line of storms.

After the Butler county hail report, the squall line weakened slightly and the new storm intensified. The squall line was moving from 290 degrees at around 26 kts, while the new storm was moving from 318 degrees at 23 kts. The mesocyclone associated with the new storm was not strong (greater than 40 kt rotations) but it did exhibit persistence. At 0650 UTC, hail up to the size of baseballs (2.75 inch diameter) was reported near Garland, NE. This was associated with an impressive reflectivity core of greater than 65 dBZ between 8,000 and 28,000 feet in the KOAX WSR-88D Reflectivity Cross Section (Figure 6). Large hail may have occurred earlier, but no reports were received. At 0655 UTC, the highest VIL value was 75 kg/m^2. The VIL gradually increased during the next eleven minutes, and reached a maximum of 80 kg/m^2. At one point there were five "pixels" greater than 70 kg/m^2 (Figure 7).

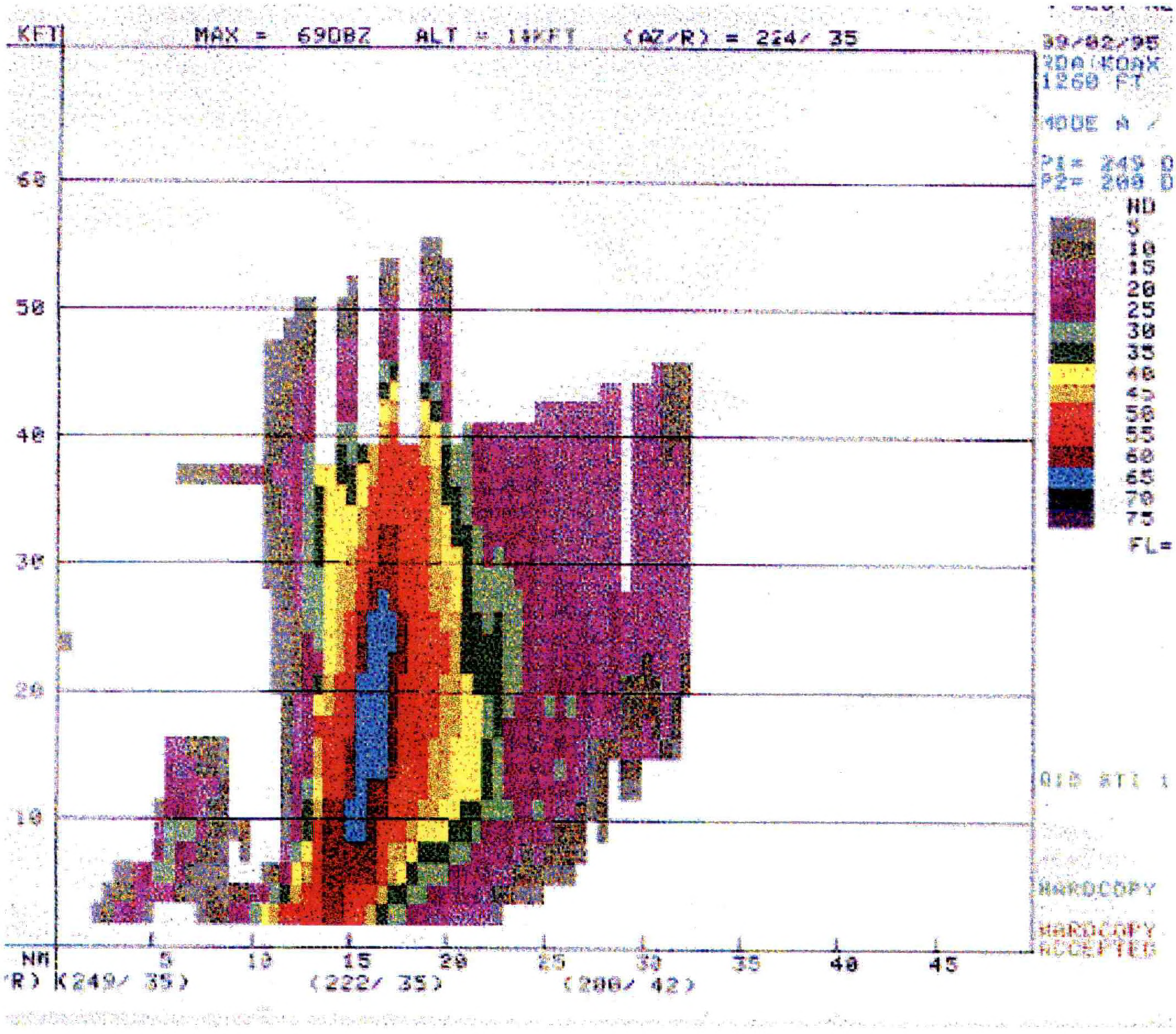

Figure 6. 0655 UTC 2 September 1995 Reflectivity Cross Section through the storm from the KOAX WSR-88D. *Note* the large area of greater than 65 dBZ that extended from 8,000 to 28,000 feet.

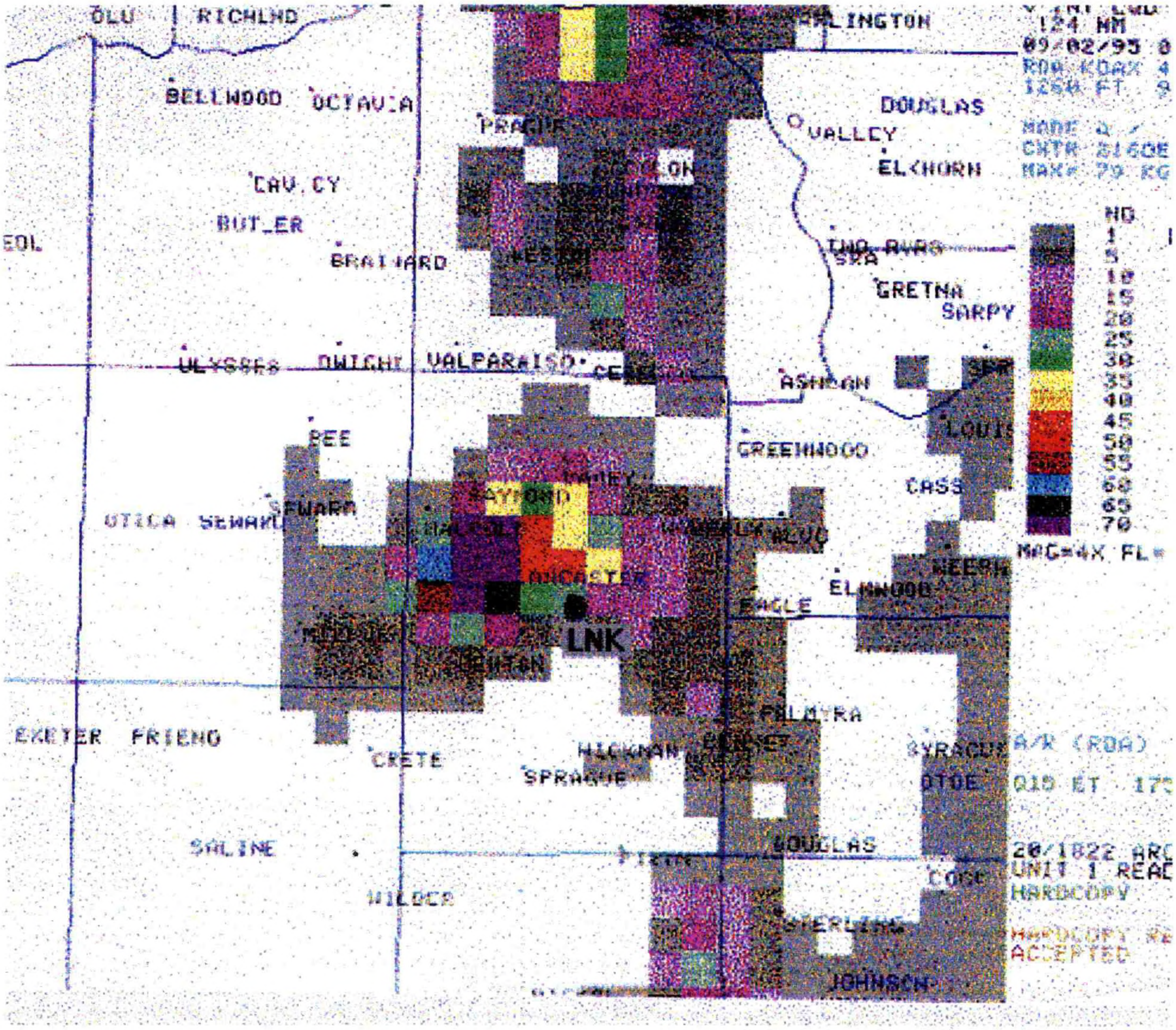

Figure 7. 0706 UTC 2 September 1995 Vertically Integrated Liquid (VIL) from the KOAX WSR-88D. The area northwest of Lincoln, NE (LNK) has five pixels of 70 dBZ or greater.

Shortly after the VIL value of 80 kg/m^2 was observed, hail up to the size of softballs (4.50 inch) was reported 6 miles west of downtown Lincoln, NE. Only one other hail report was received, which was 1.00 inch diameter hail within the city of Lincoln. After this, the storm weakened rapidly. This could have been because thunderstorms were developing farther south in Kansas, which reduced the inflow from the low level jet. Also, the storm was encountering less low level moisture and higher stability as it moved east.

Total damage was at least $140,000 (value obtained from September 1995 **Storm Data**). The property damage could have been much greater, but fortunately the large hail mainly fell in sparsely populated areas. If the city of Lincoln had taken a direct hit, the damage could have been several million dollars. For a summary of severe weather reports in the NWSFO Omaha CWA, Table 3.

Table 3
This is a chronological summary of storm reports received in the Omaha county warning area on September 2, 1995.

Storm Reports from September 2, 1995 in the NWSFO Omaha CWA

Location	Time	Event	Estimated damage
Butler County			
3N Ulysses	0530 UTC	Hail 1.00	Unknown
Seward County			
Garland	0650 UTC	Hail 2.75	$100,000
Lancaster County			
3N Malcolm	0657 UTC	Hail 1.75	Unknown
Malcolm	0700 UTC	Hail 2.00	$20,000
6W Lincoln	0715 UTC	Hail 4.50	$20,000
Lincoln 0717 UTC	Hail 1.00	Unknown	

5. SUMMARY AND CONCLUSIONS

The development of elevated thunderstorms is one of the most difficult events to forecast. Careful examination of available surface and "upper level" parameters, and interpretation of sounding data between upper air sites, is needed to enhance forecast accuracy. Procedures should include isentropic analysis.

Satellite imagery showed the development of mid level cloudiness over the area. Data received from the 0000 UTC analysis and ETA model run suggested that deep-moist convection was possible. Moisture, instability and lift were all present. Multicell "pulse" type thunderstorms developed, but the severe weather associated with these storms was sporadic and short-lived.

Lift was locally enhanced along a westward moving outflow boundary, which led to the development of a new storm. The movement of the new storm was different from (to the right of) the cell movement associated with the squall line. The new storm exhibited supercell characteristics. Typically, elevated thunderstorms do not produce tornadoes, but they can produce large amounts of hail. In this case, very large hail formed because of a strong and persistent updraft, in combination with a favorable vertical wind shear profile. Because WSR-88D data was interpreted correctly, meteorologists were able to issue timely warnings with a 1.00 POD (100% Probability of Detection).

In September 1995 the maximum displayable VIL value at KOAX was 80 kg/m^2, so the actual maximum value associated with the elevated supercell discussed in this case study may have been higher. Currently, the maximum displayable VIL value at OAX is 100 kg/m^2. The request to change this value was made to the Operational Support Facility (OSF) partially because of this storm. The OSF graciously granted the request.

6. ACKNOWLEDGEMENTS

The author would like to thank Steve Byrd, Science and Operations Officer at NWSFO Omaha/Valley and Ed Berry, CRH SSD for their careful review of and input to this paper.

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