Tracking the Development of the Record Hail Event and Supercells of Nebraska, June 22-23 2003

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Case Study - AOS 453

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Abstract

Over the period of 22-23 June 2003, a convective outbreak resulted in two distinctly notable supercells in Aurora and Deshler, Nebraska. The northern cell tracked northeast through Hamilton County and was responsible for the largest recorded hailstone (7 in.), as well as heavy rainfall and weak tornado reports. Roughly 50 miles to the south, a more tornadic supercell remained persistent over Thayer County, producing an F2 tornado in Deshler, as well as three other tornadoes in the county. This case study aims to explain the synoptic and mesoscale features that conspired to initiate these severe thunderstorms, as well as the anomalously large background instability that characterized this event. Storms from the previous day moved east into Missouri and Iowa by 18z 22 June, leaving a west-ward propagating outflow boundary that became important in moisture convergence. Also important to the setup of this event was a strengthening low level jet, which intensified around 00z 23 June to advect high dew point temperatures to the central Midwest region. In the presence of daytime heating and agricultural evapo-transpiration, the outflow boundary served to channel the moisture into the central Nebraska and north central Kansas region, destabilizing the ambient environment. With upper level conditions favorable for upward vertical motion, the outflow boundary approached a north-south oriented quasi-stationary surface front in central Nebraska and triggered convective cells in Aurora and Deshler.

Introduction

June 22-23 2003 proved to be a memorable severe weather event for the north central midwest U.S., especially for Aurora and Deshler, Nebraska. In the evening hours of 22 June, two distinct supercells formed and produced record-setting amounts of hail and rainfall, along with severe tornado damage. Both storms had very different characteristics, with the northern cell being primarily hail-producing, and the southern cell being more tornadic in nature. As the northern cell tracked to the northeast, it dropped huge amounts of hail on Hamilton County, including the biggest hailstone ever measured, at 7 in. (17.78cm), Aurora, NE. Fifty miles to the south on the Nebraska/Kansas border, the southern cell remained stationary for nearly 6 hours, dropping almost a foot of rain on Deshler (Fig 1) and spawning 4 tornados in Thayer County.

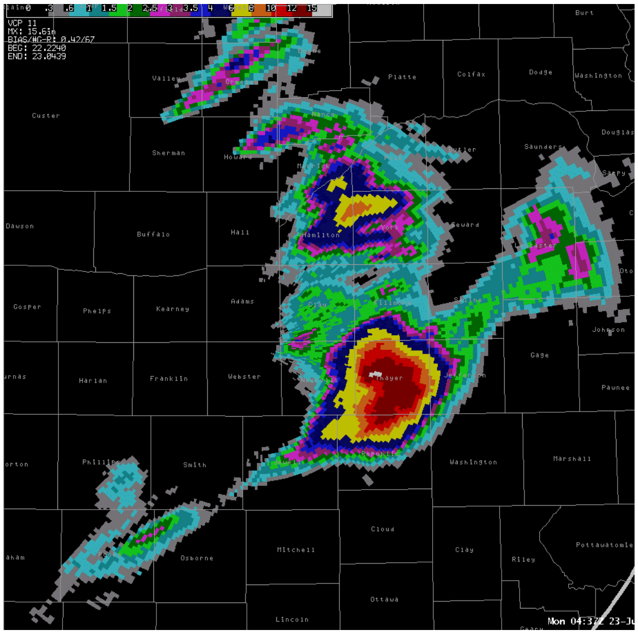

Figure 1: Storm Total Precipitation (in.) Bullseye over Thayer County, NE

As a result of the giant hail from the northern supercell, the National Climatic Data Center (NCDC) estimated property damage to be around $500,000, with crop damage nearing $1 million. The size and speed of the falling hail left craters in the ground that measured 14 in. in diameter and 3 in. deep). The record-setting hailstone had even fallen through a house roof before being measured, so it may be an underestimate of the magnitude of hail produced by this storm. In a study of hail size predictability, the HAILCAST model determined an average hail size of 3.1 in. based on initial conditions from the 00z 23 June Aurora sounding (Guyer 2004). Although this underestimates the actual size measurements, it is much greater than the 1 in. hail size requirement necessary for a "severe" thunderstorm (NWS IA/IL).

Tornado, wind, and flooding damage was extensive for Thayer, NE, Jewell, KS, and Republic, KS counties. The National Oceanic and Atmospheric Administration's Storm Prediction Center put out 15 tornado reports and eight wind reports for the Nebraska/Kansas region on 22 June.

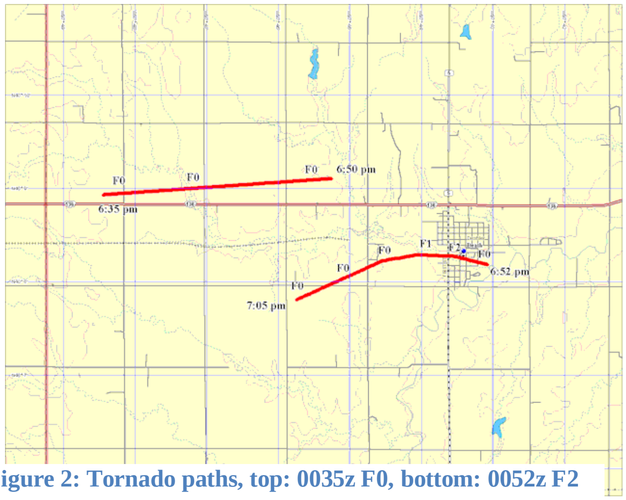

Figure 2: Tornado paths, top: 0035z F0, bottom: 0052z F2

The first F0 tornado touched ground at 0035z west of Deshler where it moved east-northeast for 25 minutes before dispersing (Fig 2). Immediately after, an F2 appeared directly southeast of the city where it tracked west and southwest for 13 minutes, finally dying out after 01z 23 June (Fig 2). More than 100 homes and nine businesses were damaged or destroyed from the tornado, and there were also many downed power lines, windswept barns and trailers, and uprooted trees. Seven people were injured and one person died, the first tornado death in Nebraska since 1988 (NWS- Hastings, NE)

Intense supercells such as those on 22-23 June 2003 are relatively infrequent, however many environmental factors proved to be extremely favorable for severe thunderstorm development in this particular event. A full analysis of these conditions will follow, however it is useful to review a general conceptual model of such supercells to see how this case compares to the textbook picture (Fig 3).

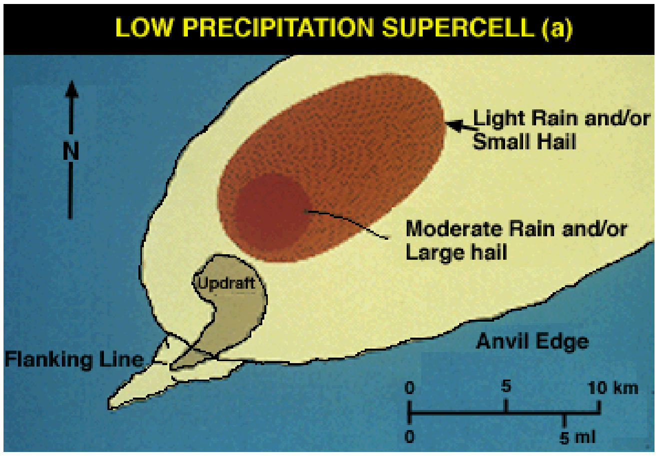

Figure 3: Low-precipitating supercell conceptual model, University of Illinois Weather World 2010

Obviously the northern cell was responsible for the largest hail reports and hail damage, and its radar echoes most closely resemble a low-precipitating, large hail-size supercell structure (Fig 9).

Supercells form in the presence of unstable environments, with speed and directional wind shear. When horizontal vorticity is generated by the vertical wind shear, the updraft tilts the vorticity into the vertical, producing a mesocyclone at the core of a vertically tilted storm. Once the heavy precipitation associated with the storm is horizontally displaced from the core updraft and downdrafts, it can continuously sustain inflow to the updraft without processes like evaporative cooling or precipitation drag to cut off the buoyant updraft. In low-precipitating supercells such as Figure 3, a dry layer at mid levels and slightly lower precipitable water content leads to less water loading of the updraft.

Condensation nuclei such as ice crystals, frozen rain, dust, aerosols, or even insects that are present in the storm environment can get caught in the up/down draft cycle to facilitate hail formation. With stronger upward vertical motions in the updraft, these particles come into contact with supercooled water near the top of the cloud. Depending on the temperature and saturation conditions, the liquid water can either slowly cover the particle until it freezes in a clear layer, or immediately freeze onto the nuclei in a cloudy layer. The gravitational pull of the growing hail nuclei eventually outweighs the strength of the updraft and it falls in the downdraft portion of the storm circulation (NWS).

For the Aurora supercell of 22 June 2003, the updraft was extremely strong, so that turbulence inside the storm core caused the hail particles to circulate between the up and down drafts for an extended period.

According to the National Weather Service (NWS), updraft speeds of almost 50 m/s are necessary to grow a hailstone to “softball” size, or 4.5 inches. Obviously the 7 in. Aurora hailstone required a stronger updraft speed, so we can examine the Convective Available Potential Energy (CAPE) to determine how much of the potential energy is converted to kinetic energy of the updraft. Through a NWS bulk formula, the updraft speed is determined by taking 2 times the square root of CAPE, and adding the Storm-Relative Inflow in knots. The factor of 2 is kept outside of the square root of CAPE to compensate for such factors as entrainment (NWS – Wichita, KS). Given a CAPE value of 3712 J/kg from the 00z 23 June North Platte, NE sounding, and a sfc-2km Storm Relative wind of 18 knots, the NWS formula gives an updraft speed of 71.5 m/s. Qualitatively, this seems like a reasonable value for an updraft to grow large hailstones such as those from the 22 June 2003 Aurora supercell.

It is interesting to note that the record hailstone was actually irregular in shape, which suggests that it was an aggregation of two separate hail stones which had collided with enough force to fuse into one large stone (NCDC).

The Deshler supercell on the Nebraska/Kansas border contained the most intense mesocyclone ever recorded by single-Doppler velocities (Wakimoto 2004). This is consistent with the tornadogenesis that occurred across Thayer County around 00z 23 June, however the strength of mesocyclones is not always indicative of tornado frequency or intensity. The LP-supercell conceptual model will be less applicable for this cell; a classic or high-precipitating supercell would be more representative of the Deshler supercell structure. Also known as "rain-wrapped" supercells, the strong rotational characteristics of these storms cause the precipitation core to wrap around the mesocyclone. The abundance of moisture throughout the cell can cause heavy rain and subsequent flooding, especially when the storm remains stationary, as the Deshler supercell did.

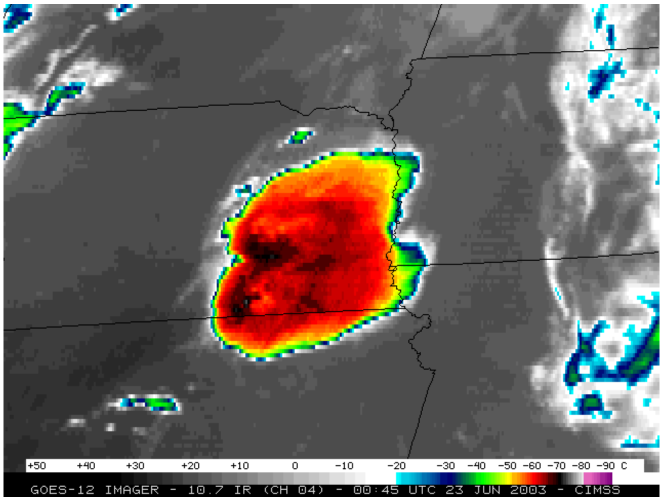

Figure 4: GOES-12 10.7 µm IR image, 0045z 23 2003. CIMSS

The infrared satellite image of eastern Nebraska 00z 23 shows the intense convection of both storms, with overshooting domes visible at cloud tops of around -70°C. The outflow boundary of the supercells extends into Kansas, Iowa, and Missouri, another testament to the intensity of the storms' circulations (Fig 4).

With a general understanding of supercell characteristics as they relate to the 22-23 June 2003 event, we can examine the synoptic and mesoscale features that set the stage for the these powerful supercells to devastate central Nebraska and north central Kansas. Based on information from the following data sets as well as other case studies done on this event, it was determined that the interaction of a stationary front with an outflow boundary in a region of high instability caused the extremely intense supercells that developed around 00z 23 June. From there, a dryline feature in central Kansas initiated further convection that briefly interacted with the evolving supercells to resemble more of a squall line/Mesoscale Convective System. These major points will be addressed in the following sections with brief mention of additional features that were relevant to the case.

Data

Data and figures for this paper were largely derived from National Weather Service Storm Prediction Center Reports, the Unisys Upper Air Charts Archive, the Cooperative Institute for Meteorological Satellite Studies, and the Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX). Radar data was used from the WSR-88D NEXRAD Level-II radar, while satellite images from the Geostationary Observational Environmental Satellite – East (GOES-12) were used as supplementary information. Soundings were taken from the University of Wyoming College of Engineering Department of Atmospheric Science, although some of the severe weather indices were only found on SPC archived soundings. The conceptual model was from the University of Illinois Department of Atmospheric Sciences Weather World 2010 Project.

Synoptic Overview

The synoptic setup for this event proved to be highly favorable for the development and intensification of the Nebraska/Kansas thunderstorms. The interaction of several synoptic-scale features with mesoscale processes allowed for maximum instability and significant forcing for convection. The period of 12z 22 to 00z

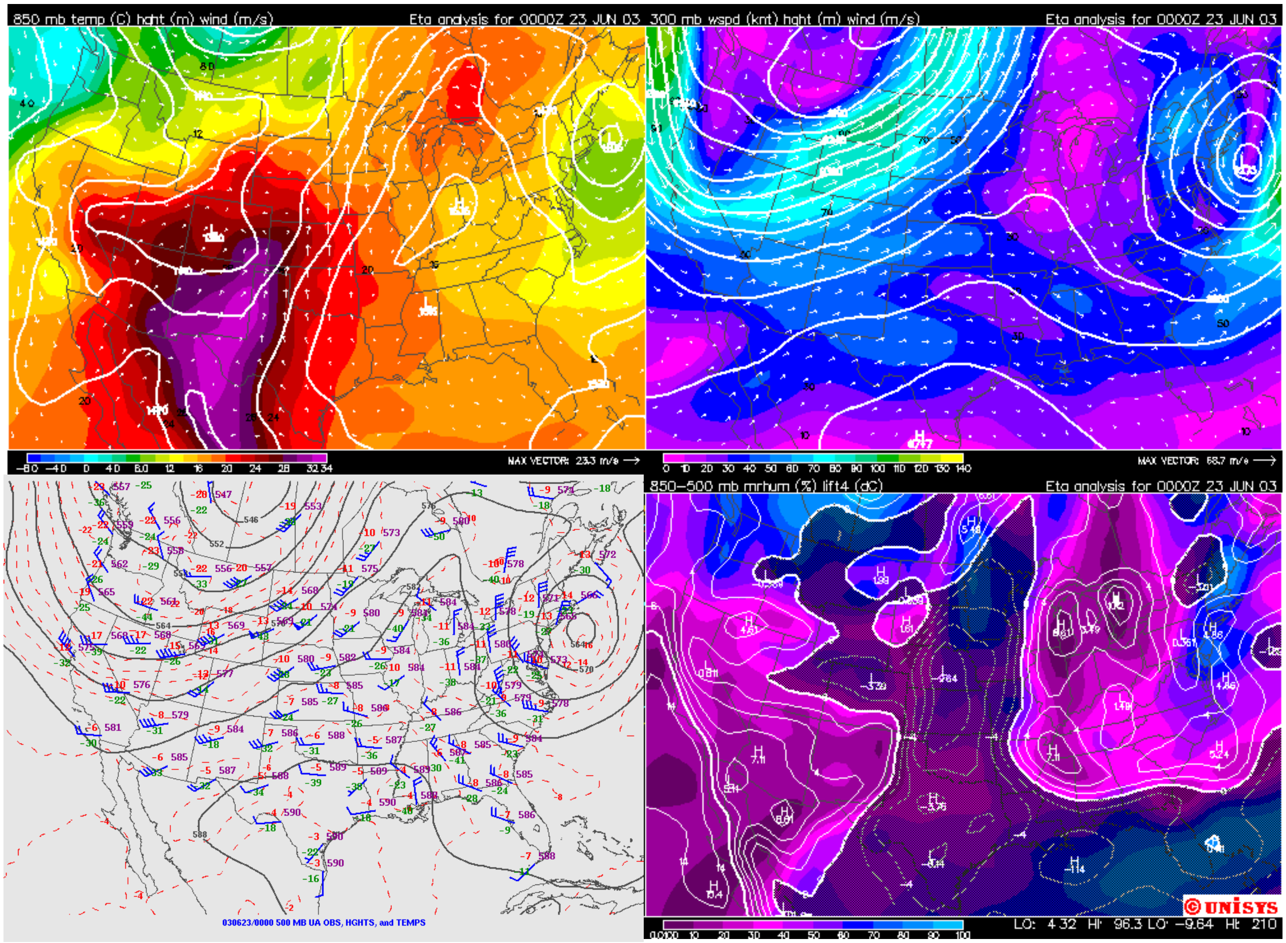

Figure 5: 4-panel synoptic maps valid 00z 23 2003: Upper right: 850 mb temperature fills (°C), geopotential height (m), wind vectors. Upperright: 300 mb wind speed fills (knots), geopotential height contours (m), wind vectors. Lower left: 500 mb upper air obs, solid geopotential height contours, dashed temperaturecontours. Lower right: 850-500 mb Relative Humidity (%), Lifted Index (C).

23 June is when many of these interactions came into play, so we will discuss the evolution of synoptic features from 300 mb to the surface in this time frame.

The upper tropospheric wave pattern over the United States shows the western United States dominated by a broad trough, with strongly diffluent flow across a weak ridge extending from Texas to Ontario (Fig 5, upper right). The polar jet stream rounded the base of the trough at the border of central California and Nevada, with a distinct wind maximum that extended from Wyoming to the Montana/North Dakota border with Canada. From 12z 22 to 00z 23 the jet remains oriented from southwest to northeast, so that the entire Midwest, including Nebraska/Kansas, is located in a region of anticyclonic shear. This low absolute vorticity has the effect of lowering the inertial stability of the atmosphere and accelerating the inflow/outflow circulation (Tripoli).

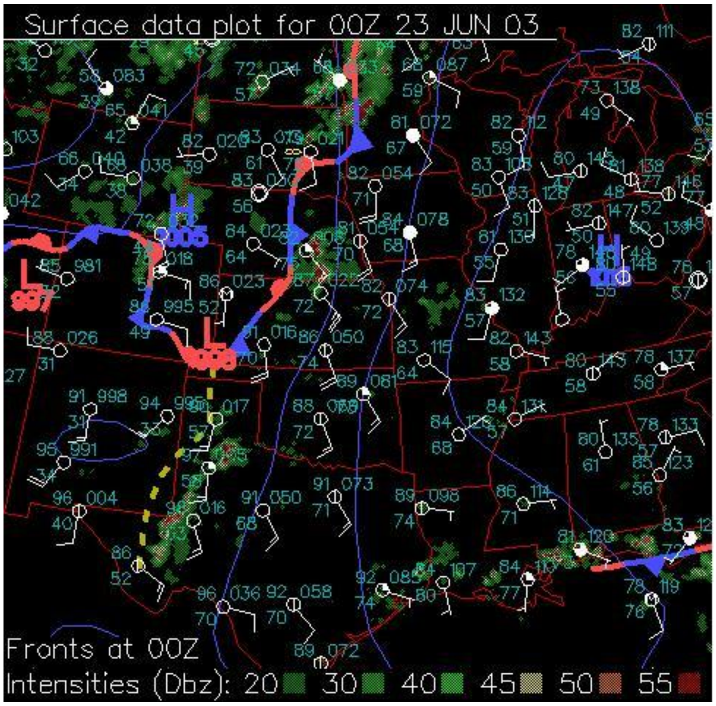

Figure 6: Surface analysis valid 00z 23 2003. Surface station data, frontal analysis, surface pressure fields

At mid levels, there were two shortwaves located over the border of central Nebraska/Kansas and in central Iowa (Fig 5, lower left). The upward vertical motion in the exit sector of these vorticity maximums likely contributed to the intensification of the Nebraska supercells. After 12z 22, the 500 mb flow becomes more westerly and slightly faster.

In the lower troposphere, the flow turned from southerly to southeasterly by 00z, and a strong baroclinic zone developed from southern Texas to central Nebraska (Fig 5, upper left). This drew large amounts of moisture from the Gulf of Mexico and supplied humidity to the entire air mass over the central Midwest (Fig 5, lower right).

At 12z 22, the surface analysis places a quasi-stationary frontal boundary from Western Colorado north through Manitoba. This became an important feature in the initiation of the thunderstorm outbreak, and by 00z 23 the front was positioned directly through north central Kansas/Nebraska (Fig 6). This boundary marked the western edge of the central plains region of high instability. Dew point depressions went from 7°C east of the front to 20°C on the west. Wind shifts farther north on the frontal boundary were also indicative of the different air masses that were mixing over the Midwest.

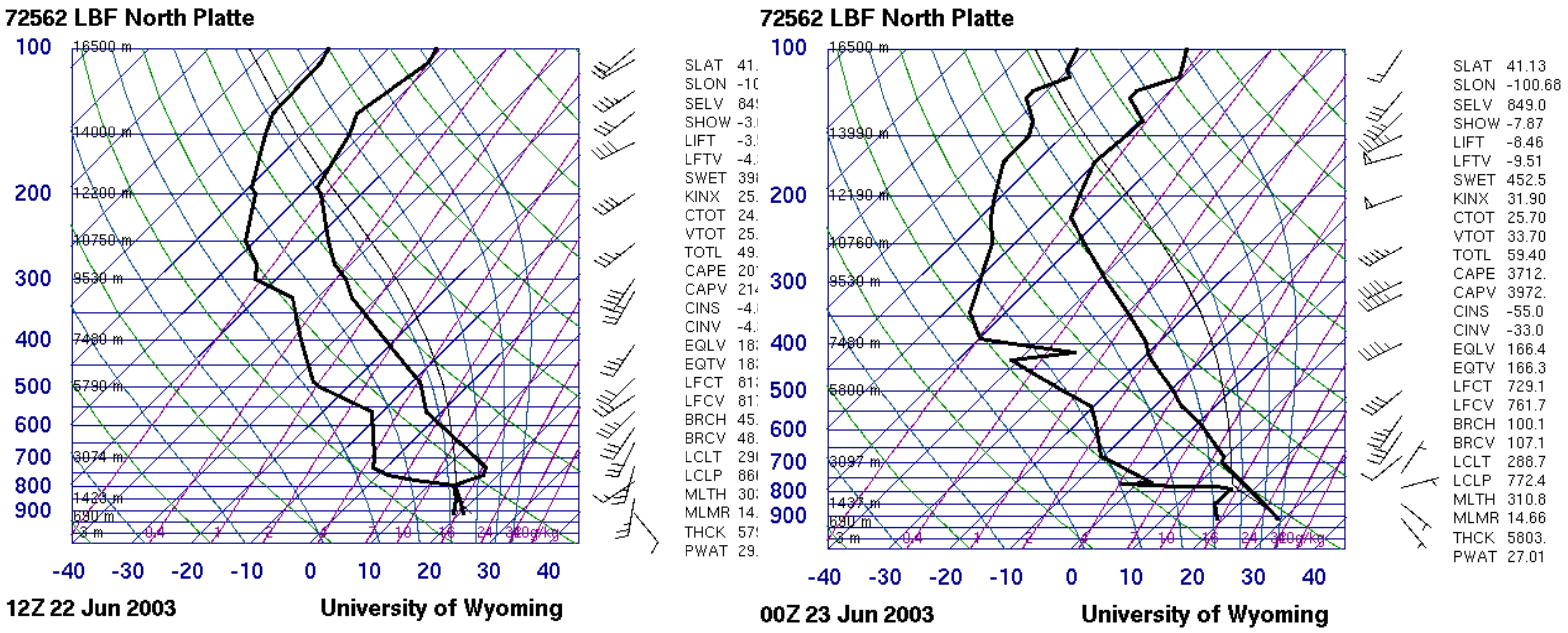

Figure 7: Atmospheric upper air soundings: North Platte, Nebraska. Left: 12z 22 June, Right: 00z 23 June.

An additional large-scale feature that is generally significant in contributing low-level moisture to the atmosphere is agricultural evapotranspiration (Tripoli). This process accounts for moisture evaporation from soil and vegetation surfaces as well as the loss of water vapor through plant stomata (Bernacchi, 2006). For the United States Corn Belt, late June is in the middle of growing season, so this "corn-fed" air mass was one factor that ramped up the local instability for central Nebraska and northern Kansas.

Mesoscale Analysis

While the large scale flow patterns contain several ingredients that assisted storm development, it was the mesoscale environment of late afternoon 22 June 2003 that determined the severity of the Aurora and Deshler supercells. With the help of a southeasterly low level jet, a west-moving outflow boundary, and the quasi-stationary surface front, local background instability grew as the day progressed. After the major convective outbreaks associated with these supercells, dryline convection played a role in the evolution of the entire system through the morning hours of 23 June. By looking at each of these features during the period of supercell formation, we can explain the development of these storms. The type of each supercell also relates to the observed lightning characteristics, which will be discussed at the end of the mesoscale analysis.

Instability

First we will consider the atmospheric conditions around the high region of instability in central Nebraska. Radiosonde soundings from North Platte, NE at 12z 22 and 00z 23 are utilized to understand how the vertical structure of the troposphere might have affected storm development (Fig 7). The temperature and dew point profile along with wind vectors will also allow for the calculation of various severe weather indices. After discussing physical properties of the soundings, some of the conventional indices will be mentioned to give a quantitative idea of the strength of these storms. These indices are useful not only for determining severity of a thunderstorm, but also the type of storm that will develop (shear vs. CAPE).

At 12z 22, a nearly saturated boundary layer existed from the surface up to 800 mb. Moisture from previous thunderstorms in the area and the evapotranspiration mentioned previously provided reinforcement to the mean southeasterly flow carrying Gulf air to the central plains. A strong inversion was present from 800-750 mb, and a wind shift to southwesterly suggested that a dry, well mixed air mass was being advected from the desert southwest. This capping inversion represents -134J/kg of negative buoyancy that must be overcome by lifting mechanisms in order for surface parcels to experience free convection (SPC). Already at 12z there was a significant amount of CAPE (2291 J/kg), with a nearly adiabatic lapse rate at two different layers (750-525 mb & 500-325 mb). Strong wind shear in the lower atmosphere indicated a favorable environment for supercellular development. This will be addressed more thoroughly in the context of severe weather indices.

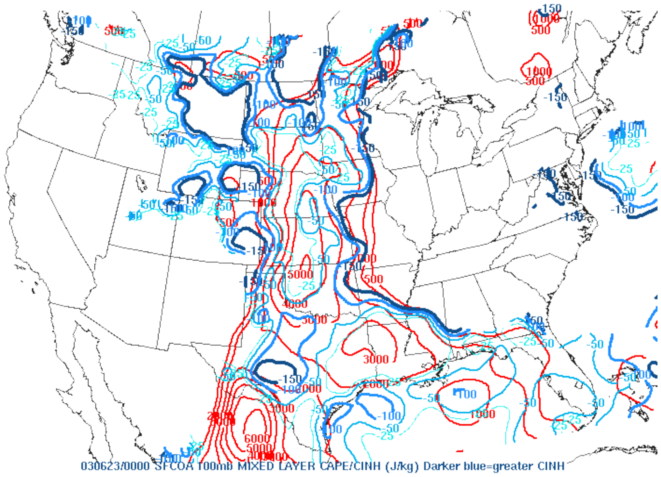

Figure 8: SPC outlook for Mixed Layer CAPE/CIN, contours of J/kg CAPE/CIN, valid 00z 23 June 2003

Strong surface heating between 12z 22 and 00z 23 occurred throughout the central plains, with temperatures warming into the 30’s and dew points in the 20’s for south central Nebraska and north central Kansas (Fig 7, right). By 00z 23, the warm flux of low level moisture resulted in a conditionally unstable atmosphere with a near dry adiabatic lapse rate extending to the tropopause. Low level wind shear increased with the passing of the frontal boundary, so that convective outbreaks formed the rotating updraft characteristic of supercells.

As the surface approached the convective temperature, low level mixing and convective overturning ate away at the 800 mb inversion, and the lifting due to low level convergence provided adequate forcing to break the cap and produce the powerful supercells in the evening of 22 June. The specific forcings that aided convergence will be discussed in the proceeding section.

The anomalously large instability of this event can be further quantified by the value of various severe weather indices. CAPE has already been mentioned in terms of the updraft speed, and the maximum value in the region of supercell development was over 4000 J/kg (Guyer 2004). Figure 8 shows the SPC analysis of mixed layer CAPE/CIN for 00z 23 2003. The region of storm development in central Nebraska/Kansas is located in the bullseye of largest CAPE values, with low CIN values easily overcome by forcing for lift. With this kind of positive thermodynamic energy available to lifted air parcels, the storm experienced deep convection, with cold, overshooting cloud tops around -70 (Fig 4). The lifted index (LI) is a similar instability measure which compares the environmental temperature to the parcel temperature at 500 mb. With an LI of -8.5, air parcels at 500 mb were almost 9°C positively buoyant and continued to accelerate upwards until reaching the equilibrium level (EL). From SPC, the 3km helicity was 261 m^2/s^2, which indicates that the low level shear produced significant rotational effects, possibly encouraging tornadogenesis. Other indices also indicate potential for widespread and severe thunderstorms as well as tornados: Showalter Index: -7.87, Totals total: 59.4, SWEAT: 452.5.

Outflow Boundary

The main mesoscale feature that initiated convection was an outflow boundary, which actually resulted from thunderstorms on the previous day. As late evening and overnight storms on 21 June dissipated and moved off into Iowa/Missouri, they left a linear, north-south outflow boundary in eastern Nebraska. Although this weather had passed 12-24 hours earlier, the westward propagating surface outflow remained well organized, reaching central Nebraska by 00z 23 June (Fig 9). As this boundary reached the surface stationary front it decelerated, pooling the boundary layer moisture and creating an instability axis over the central plains. The outflow provided an eastern border for the warm humid air mass that was advected into the region from the Gulf of Mexico. With the quasi-stationary frontal boundary to the west, the effect of the low-level southerly flow was to channel moisture into the instability axis over eastern Nebraska. Once this forcing had strengthened later in the day, convergence in the region of the stationary front and the outflow boundary provided a lifting mechanism to break the cap and initiate convection just east of the outflow around 2230z 22 June.

Low Level Jet

As alluded to previously, the low level jet is a key component to the continued supply of warm, moist air from the Gulf region. This nocturnal feature is common to the central Great Plains region when radiative cooling of the west plains creates a pressure surface sloping up to the east. The associated pressure gradient creates an east to west wind maximum, which turns to the north under the coriolis force. In the early morning hours (12z) of 22 June, this jet

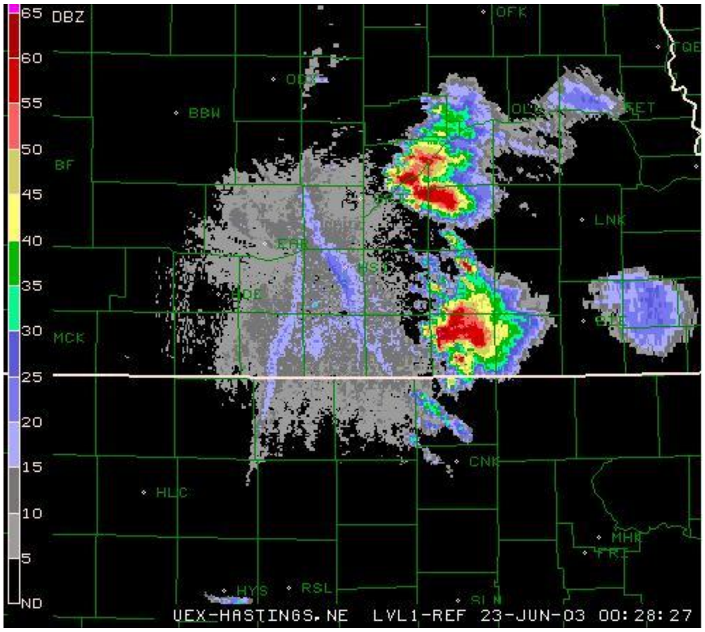

Figure 9: 0023z 23 June, Hastings, NE UEX radar reflectivity (DBZ)

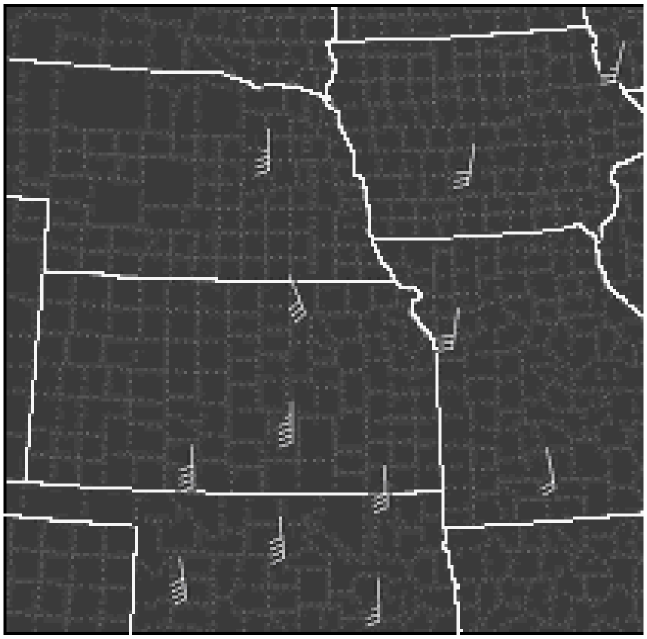

Figure 10: Airfield Ground Lighting (AGL) network wind observations, 875mb 0300z 23 2003.

feature was set up around 875 mb over Oklahoma, Kansas, and eastern Nebraska. During the night and morning hours of 22 June, the sustained 40-knot southerly flow supplied the moisture that fed the storms which ultimately left the outflow boundary discussed earlier.

The low level jet weakened as the daytime heating of the Great Plains removed any existing east-west pressure gradients.

Towards the evening hours of 23 June, the outflow boundary reached the proximity of the surface stationary front, which concentrated the unstable air mass west of the outflow in the region of south central Nebraska/north central Kansas. As the nocturnal low level jet reformed with differential radiative cooling, large amounts of moisture were fluxed from the Gulf of Mexico into the central plains (Fig 10). This continued transport into the concentrated instability resulted in lots of moisture convergence directly below the supercell outbreak.

Miller Diagram

A Miller diagram will be useful to visually understand the interacting features around the time of the supercell outbreaks (00z 23 June 2003). Originally developed by Robert Miller and Ernest Fawbush in 1948, this type of chart is useful for classifying weather events within five general categories of synoptic setup (Miller 1972). As the author's diagram indicates (Fig 11), the set up of major features in the central plains resembled a type C miller diagram pattern.

A low level moisture tongue advected by the nocturnal jet from the gulf region covers the central midwest. Above this boundary layer moisture lies a distinct dry layer from the desert southwesterly flow. In central Nebraska, the convergence of the surface stationary front and the outflow boundary in the highly unstable atmosphere was the main trigger for rapid storm development. The low level and upper level flow vectors give an indication of the wind shear profile which is also seen on the 00z 23 June sounding. The 500 mb shortwave trough axis is oriented from northwest to south east, and lies directly on top of the convection outbreak region. As discussed earlier, this forcing for positive vertical motion no doubt aided the intensity of the convection once the cap was broken.

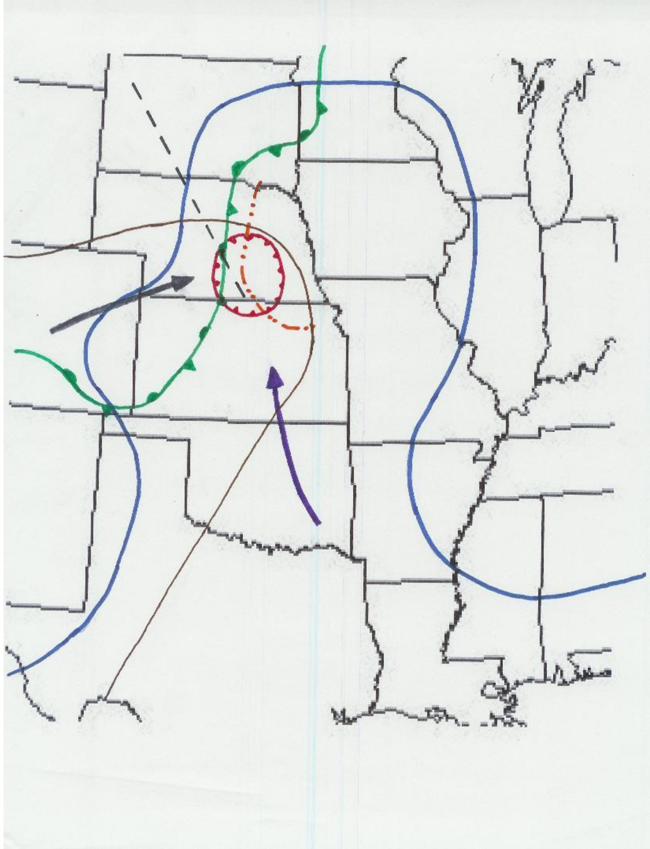

Figure 11: Hand-drawn Miller diagram valid 00z 23 2003: Low level moisture tongue (blue line), low level jet vector (purple arrow), mid level flow vector (grey arrow), mid level dry tongue (brown line), surface stationary front (green), 500 mb shortwave trough axis (dashed black line), outflow boundary (orange boundary line), region of convective outbreak (red circle)

After the initial outbreak, the supercell transition towards more organized mesoscale systems is typical of type C patterns, which often evolve towards type E squall lines (Henz).

Storm Evolution

After 0200z 23 June, the organization of the Aurora and Deshler supercells began to evolve towards a Mesoscale Convective System (MCS) (Lyons 2004). As further development of these systems occurred along outflow boundary, they remained relatively slow moving, especially the Deshler supercell. This cell actually split and reformed over Republic and Superior Counties (Fig 12, upper left) (Johnson 2006). Interactions between different storm cells intensified and they began to merge into MCS-like clusters.

Farther to the southwest of this storm cluster, the dryline in central Kansas provided a forcing mechanism for new convection to break out around 0230z 23 (Fig 12, upper right).

As the MCS complexes around the Nebraska/Kansas border became more organized, their surface cold pool strengthened (Lyons 2004). The whole complex tracked to the south and reoriented to resemble a southwest-northeast squall line. By 0300z 23, the northeast moving dryline convection came into contact with the MCS/squall line (Fig 12, lower left. The systems merged briefly before shearing off, with the south-bound complex moving into eastern Kansas and the dryline convection continuing to central Nebraska by 0900z 23 (Fig 12, lower right). By this time, the severe weather had lessened, with less frequent tornado and large hail reports after the initial dissipation of the supercells (SPC).

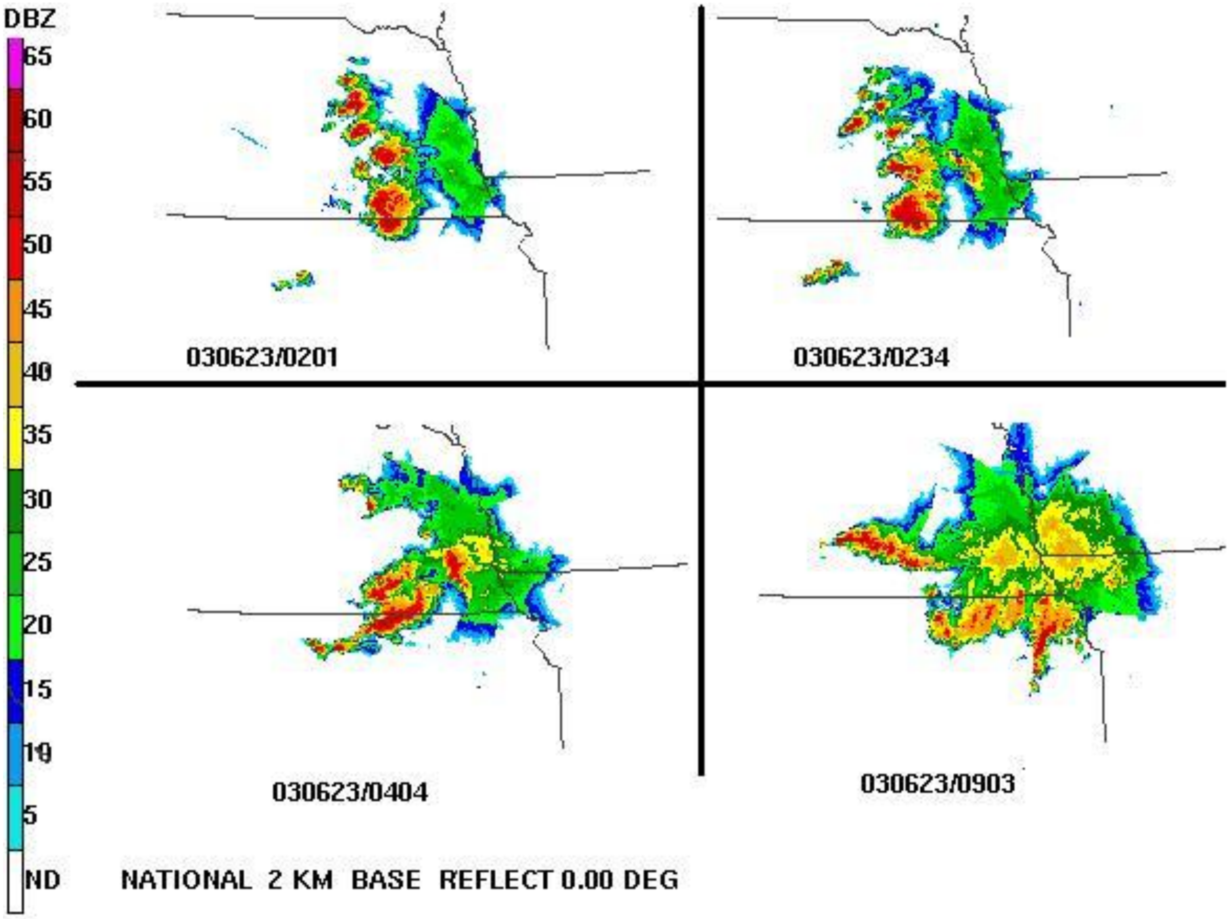

Figure 12: 4-panel SPC archived radar base reflectivity. Upper left: valid 0201z 23, Upper right: valid 0234z 23, Lower left: valid 0404z 23, Lower right: valid 0903z 23

Lightning

Another interesting perspective on the 22-23 June 2003 severe weather outbreak is cloud-to-ground lightning. It has been hypothesized that large hail cases have been associated with positive cloud-to-ground lightning, however many hail storms do not exhibit large cloud-to-ground lightning, or within-cloud lightning for that matter (Lyons 2004).

In a study of the lightning characteristics of the Aurora and Deshler supercells (Lyons 2004), it was found that both storms had an initial spike of positive strokes, which was followed by a period of negative strokes. The Aurora cell lightning had a large peak current during the positive strokes, followed by low current negative strokes when the largest hail was falling. In contrast, the Deshler cell had relatively low current, for both positive and negative lightning strokes. More research is needed to understand lightning characteristics of high CAPE/dewpoint thunderstorms with high cloud bases, such as those of 22-23 June 2003.

Conclusion

The severe weather outbreak over the central plains of 22-23 June 2003 proved to be a memorable event with just the right combination and timing of several environmental factors. From the large-scale synoptic wave pattern to the mesoscale interactions of storm clusters, the formation and intensification of the Aurora and Deshler supercells was examined.

In the upper level flow, several short waves over Nebraska/Iowa and low inertial stability southeast of the jet streak provided forcing for vertical motion and a path for outflow. A mid level desert mixed layer was advected from the southwest, and a baroclinic zone developed from Texas to Nebraska at 850 mb. Towards the surface, a north-south stationary front in central Nebraska moved slowly eastward. Although a moderate capping inversion was present from radiative cooling, a large flux of daytime solar radiation helped to destabilize the lower troposphere. The diurnal solar cycle also played a role in establishing a nocturnal jet which fed the initial outflow boundary as well as the intensification of the Nebraska supercells. When the outflow boundary moved into east central Nebraska and decelerated, the low-level convergence in the proximity of the stationary front triggered the convective outbreak in the cold air east of the outflow. Overnight, the dryline separating moist air over the eastern plains from desert air to the west initiated further convection that merged with the evolving supercells in southern Nebraska. Severe weather weakened into the morning of 23 June, with the majority of damage and precipitation coming in the evening hours of 22 June.

It is clear that the synoptic and mesoscale environment during this storm was conducive to extreme weather conditions and the intense supercells in Hamilton and Thayer counties in Nebraska. The formation of a low-precipitating-type supercell over Aurora proceeded to drop the largest measured hailstone, with a 7 in. diameter. Weak tornado reports were also associated with this cell, but the majority of its storm reports were large hail, which is common with this type of supercell. The 7 in. record hailstone is a testament to the anomalous amount of ambient instability that was present with this event. Conversely, the Deshler supercell to the south was more classical or high-precipitating, with the most intense Dopplar-measured mesocyclone on record. This cell touched down four different tornados around the Nebraska/Kansas border and dropped heavy rainfall, resulting in seven injuries and one death.

Despite the human casualties and extensive damage to the central Great Plains, this storm provided a unique opportunity for the meteorological community to document the intense and infrequent environments under which record hail-producing supercells form.

Acknowledgements

Many other studies have been performed on various aspects of this severe weather event, and these papers were very helpful in confirming the main features of this event.

Special thanks to Dan Henz and Professor Greg Tripoli for contributing general information that was useful in analyzing this case study.

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