

# Case Study of the Record Hail Event and Severe Thunderstorm Outbreak in East-Central Nebraska on 22-23 June 2003

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## ABSTRACT

On 22-23 June 2003, the largest hail stone on record in the United States was reported in Aurora, Nebraska. It measured nearly 7 inches in diameter, with a circumference of 18.75 inches (Guyer and Ewald 2004). Along with record large hail, many weak tornadoes were also reported in southeast Nebraska and northeast Kansas. Convection was initiated around 23z on 23 June just east of Hastings, Nebraska; due east of a westward propagating outflow boundary. The primary focus of this case study was to examine the synoptic and mesoscale interaction behind the formation of an intense cluster of supercells over central and eastern Nebraska on 22-23 June 2003. Both initial supercells formed along the outflow boundary induced by thunderstorms the previous day. As surface moisture increased by way of advection associated with an early morning southerly low-level jet and evapo-transpiration with daytime heating, a favorable “loaded gun” sounding was established for supercell formation. It was found that as the outflow boundary progressed eastward toward the quasi-stationary front over central Nebraska; an instability axis was formed between the two. Both the supercells near Aurora, NE, and the supercell near Deshler, NE; were initiated by a strengthening southerly low-level jet around 00z on 23 June. Therefore, the interaction between the westward propagating outflow boundary and nose of the low-level jet initiated a release of instability in the form of supercells just east of Hastings, NE; on the eastern edge of the instability axis. The northern cell produced the largest hail stone ever recorded in the United States, while the southern cell spawned multiple weak tornadoes, large hail, and torrential rainfall.

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## Introduction

The supercell outbreak in eastern Nebraska on 22-23 June 2003 was one for the record books; in which the largest hail stone ever reported in the United States was recorded in Aurora, Nebraska. Hamilton and Thayer Counties were hardest hit with supercells that dropped the record hail in Aurora also spawned a few weak F0 tornadoes in parts of Hamilton County. Further to the south in Thayer County an F2 tornado struck the town of Deshler, resulting in the first tornado casualty in Nebraska since 1980 (NCDC). There were many more weak tornadoes reported from these supercells. The supercell that impacted Thayer County remained stationary for over 5 hours with more than 12 inches of rain reported 5 miles north of Deshler during that

5 hour period leading to extensive flash flooding from wind-driven rain. Damage ranged from roof holes and broken windows to flooded cars and structural flood damage (NCDC). The towns of Aurora and Deshler were both severely crippled by this intense supercell event and were declared state disaster areas. All inclusive damage reports submitted by the National Weather Service in Hastings, Nebraska put the property loss at nearly half a million dollars and the crop damage due to flooding and hail at over \$1 million. The author happened to be staying in Kearney, NE, at that time upon returning from vacation. Kearney is located approximately 65 miles west of Aurora and experienced heavy rain and high winds from supercells that developed and tracked across the area later on in the evening on 22 June

(around 06z on the 23<sup>rd</sup>). Brightness temperatures of the cloud tops measured -70 C (Figure 1). In such a hail producing supercell, hail commonly falls behind the forward flank gust front once it becomes too heavy to ascend in the supercells updraft after descending in the hail shaft (Figure 2).

Radar signatures from the supercells in this case indicated a clear hook echo radar signature, indicative of a rotating mesocyclone such as the one depicted in Figure 2, which will be discussed in the mesoscale analysis.

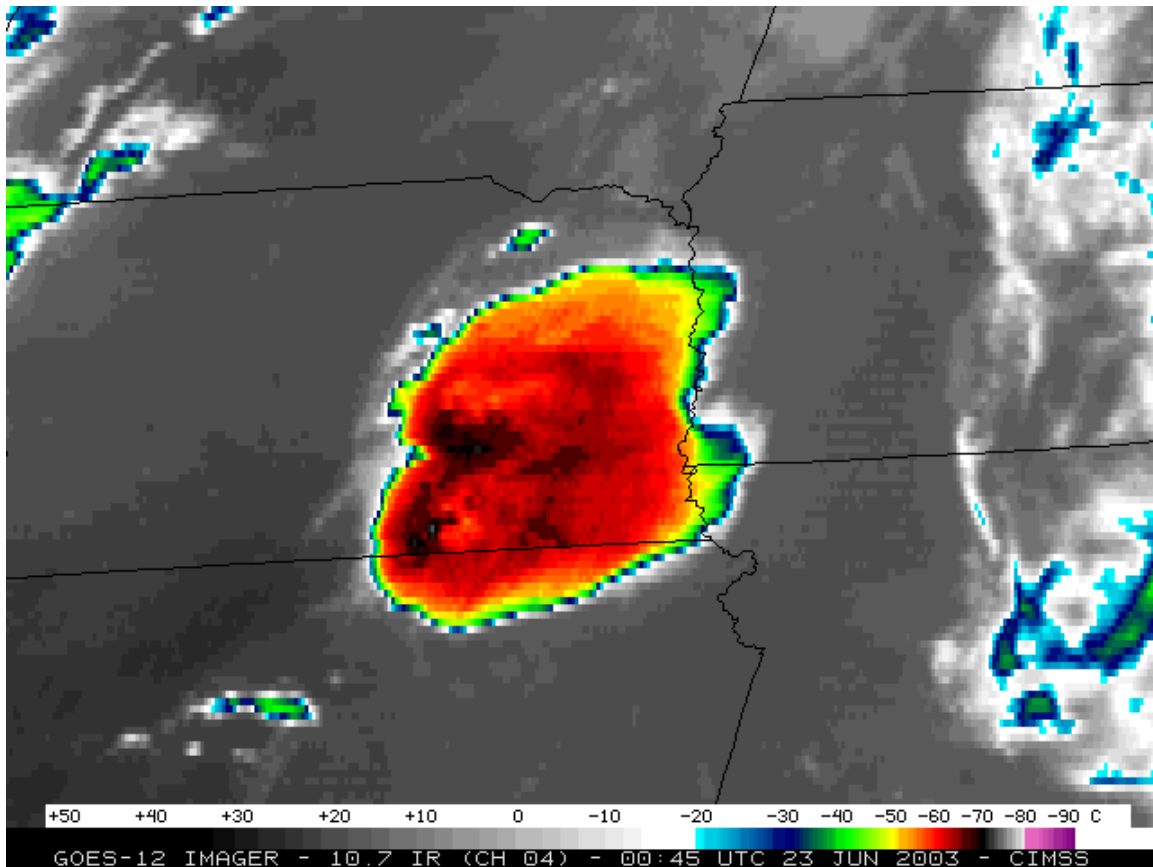


Figure 1: GOES-12 satellite image of eastern Nebraska and northeastern Kansas valid at 0045z on 23 June 2003. Convective supercell cloud tops are visible with brightness temperatures as low as -80 Celsius (C). The outflow from both the Aurora, NE, and Deshler, NE supercells extends as far east as the Nebraska-Iowa border.

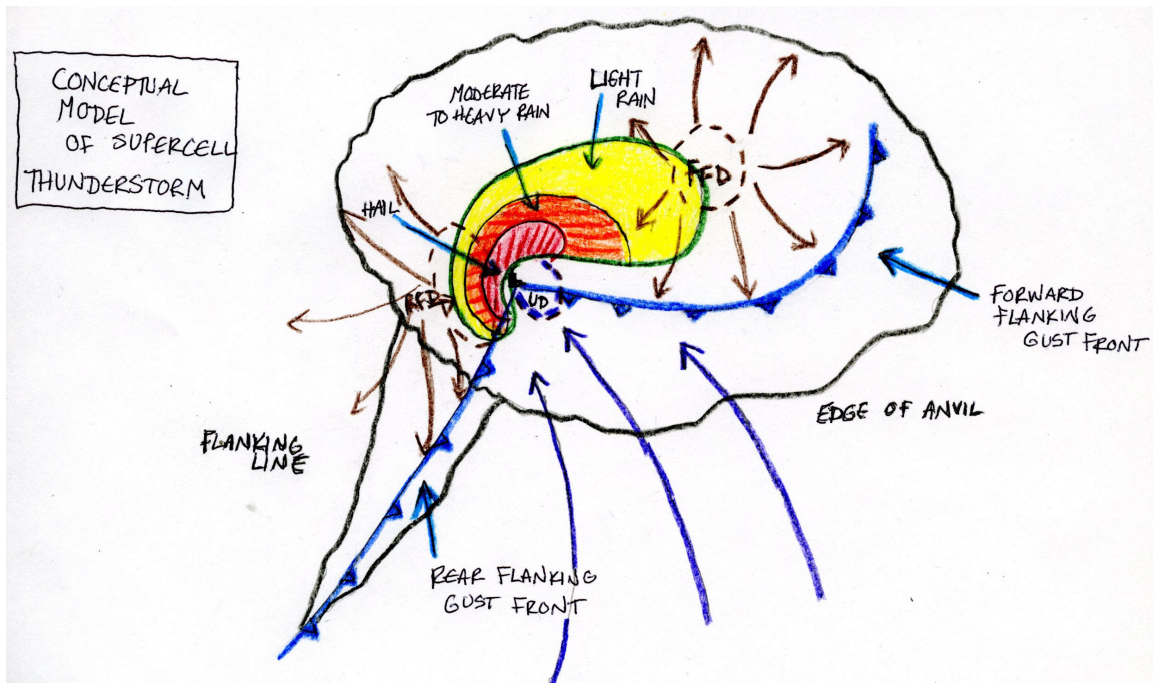


Figure 2: Conceptual model of a supercell thunderstorm as depicted by Lemon and Doswell (1979). Flow patterns associated with the forward flank downdraft (FFD) (brown), rear flank downdraft (RFD) (brown), and updraft (UD) (purple) are drawn with emphasized regions shaded for the likely occurrences of hail (red), heavy rainfall (orange), and light rainfall (yellow).

This severe weather event was initiated by coupling of synoptic and mesoscale dynamics interacting along a surface quasi-stationary front. The supercells that formed in east-central Nebraska appear to be mostly the result of mesoscale forcing but were greatly enhanced by synoptic scale moisture convergence. The main focus of this case study is to explore the mechanisms responsible for the supercell formation in central and eastern Nebraska on 22-23 June 2003. It is hypothesized that the two supercells near Hastings, NE, were initially triggered by the interaction of an intensifying low-level jet along a westward propagating outflow boundary in a region of very large instability. Subsequent supercell development was primarily the result of a further intensification of the southerly low-level jet extending from Oklahoma through Nebraska after 00z.

The most influential synoptic scale forcing was the surface southerly flow

enhancing moisture convergence along the quasi-stationary front. Also, mid- and upper-level diffluence was favorable for good thunderstorm outflow aloft. The synoptic overview of this case study will therefore focus on mid- and upper-tropospheric heights and jet streaks, lower-level moisture convergence, and the surface quasi-stationary frontal boundary. Next, the mesoscale analysis of this case will explore the role of the low-level jet in moisture transport and forcing for supercell development when coupled with the westward propagating outflow boundary from the previous evenings' thunderstorms over eastern Nebraska. Severe convection parameters will also be analyzed along with the "loaded gun" atmospheric setup for 22-23 June. Also, a look will be taken at specific radar and satellite signatures that clearly depict characteristics of both hail producing and rotating mesocyclones. Finally, a miller diagram of synoptic and mesoscale features present at 00z 23 June

will be discussed with a goal of putting together all of the pieces of the record hail supercell outbreak over east-central Nebraska on 22-23 June 2003.

**Data**

The data used for this case study was obtained from the ETA mathematical coordinate system model 12z verification on 22 June 2003 and 00z verification on 23 June 2003. This data was read into the General Meteorology Package (GEMPAK) and the Global Atmosphere Research Program (GARP) for analysis and plotting. Satellite imagery was taken from the

Geostationary Observational Environmental Satellite - East (GOES-12) at 0015z and 0025z on 23 June with 1 kilometer (km) resolution and compiled by the Cooperative Institute for Meteorological Satellite Studies. All radar imagery used was produced by the National Operational Weather radar (NOWrad) at 2213z and 2333z on 22 June and 0003z and 0103z on 23 June at the Hastings (UEX), Nebraska radar site. The hand drawn cross section implemented sounding data obtained from the University of Wyoming for North Platte (LBF), Nebraska, and Omaha (OAX), Nebraska at 00z on 23 June 2003.

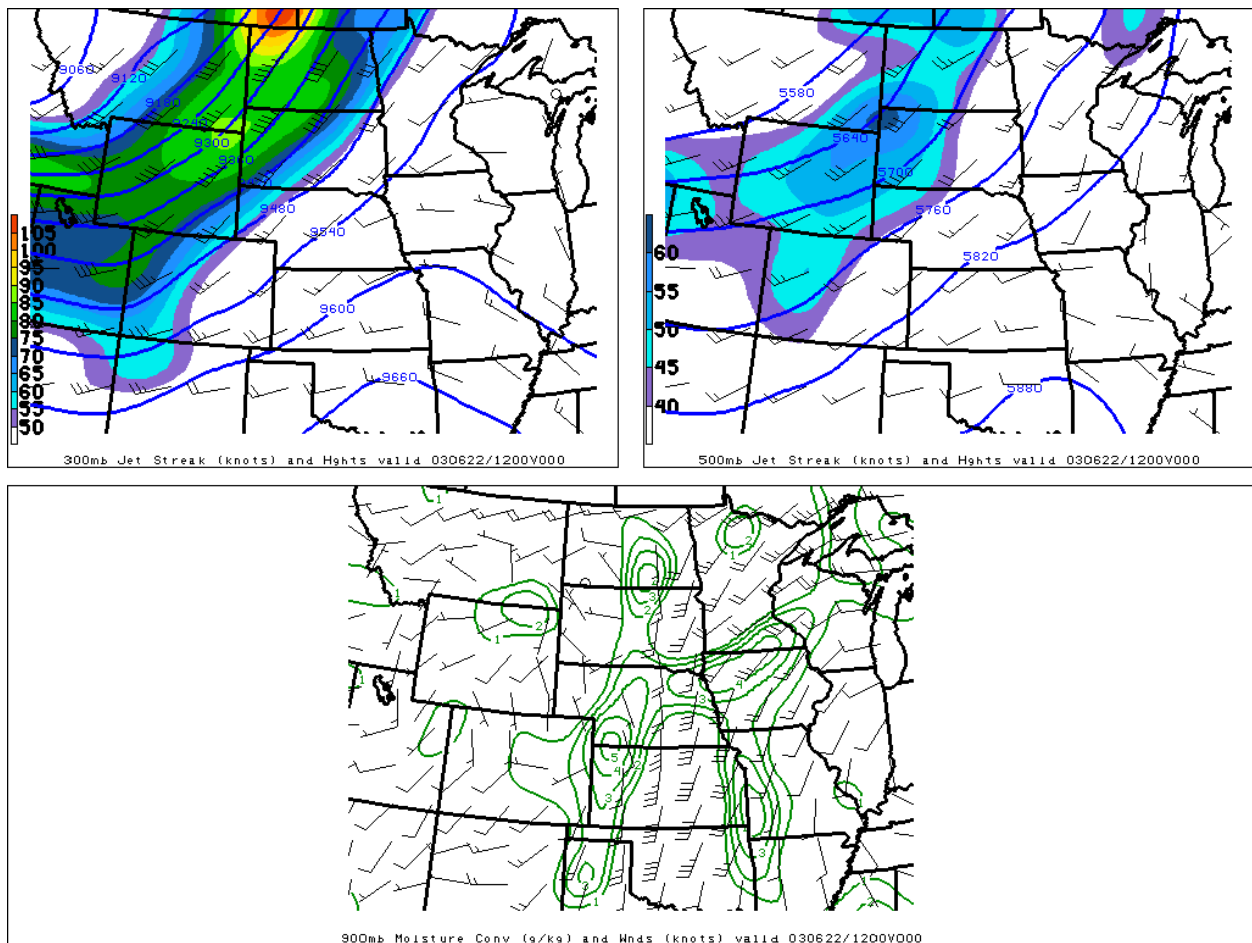


Figure 3: All plots valid at 12z 22 June 2003 with panels centered at Grand Island (GRI). (a) upper left panel: 300mb geopotential height (blue contours) and wind speed maximums in knots (fill) (b) upper right panel: 500mb geopotential height (blue contours) and wind speed maximums in knots (fill) (c) lower center panel: 900mb moisture convergence (g/kg) (green contours)

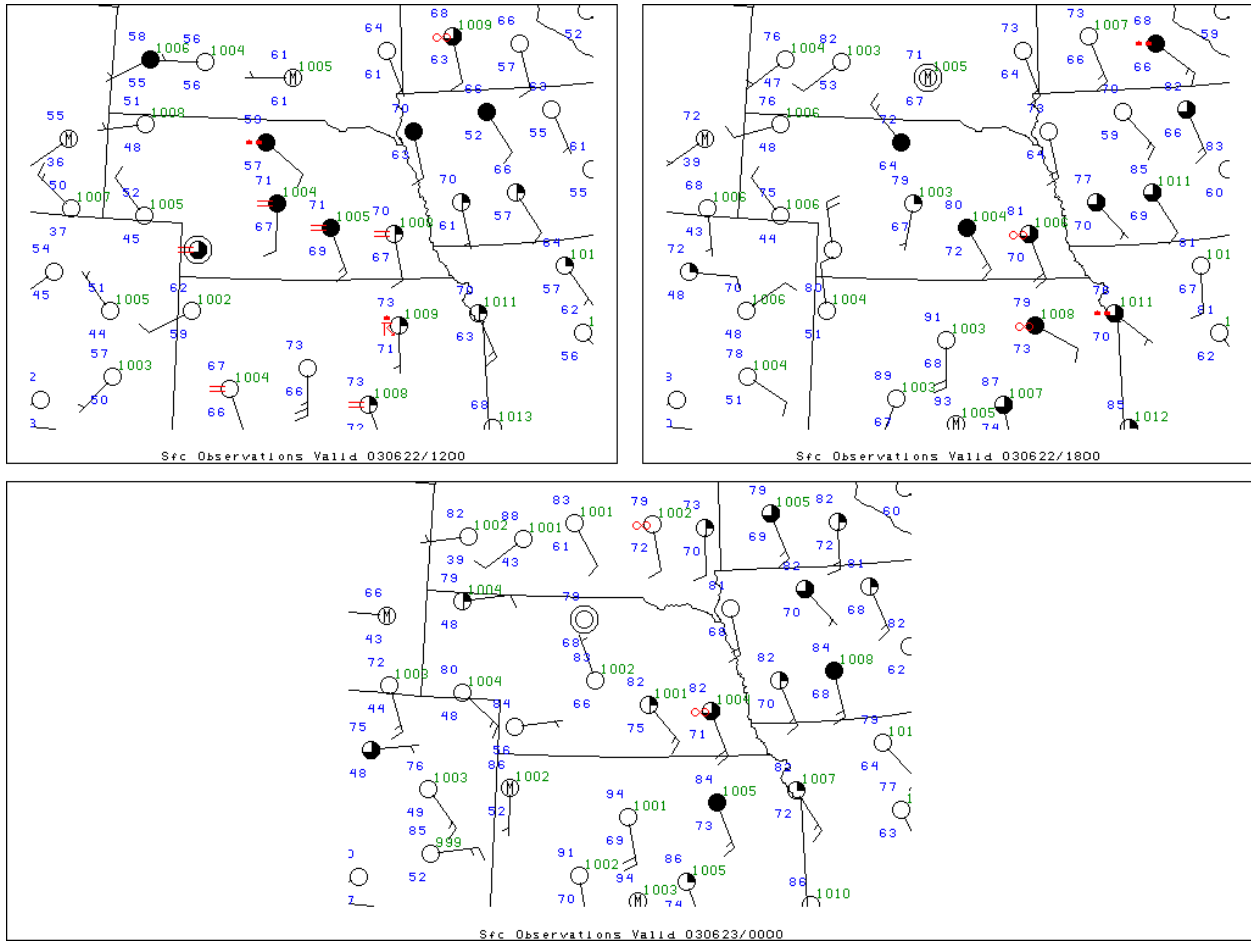


Figure 4: All panels centered at Grand Island, Nebraska (GRI). (a) upper left panel: 12z 22 June surface observations (b) upper right panel: 18z 22 June surface observations (c) lower center panel: 00z 23 June surface observations

## Synoptic Overview

### a) 12z 22 June 2003

During the early morning (12z) of 22 June 2003, a broad upper-level (300mb) trough was positioned over the Pacific Northwest, namely northern Idaho and far western Montana (Figure 3a). Associated with this upper trough was a fairly intense jet streak extending north-northeasterly from central Colorado across the western Dakotas (Figure 3a). A very shallow shortwave also is apparent with a major axis stretching from southeastern Wyoming southeast through the Texas panhandle (Figure 3a). The presence of this shortwave ultimately creates a region of weak diffluent converging flow over eastern Colorado and western Nebraska

and Kansas (Figure 3a). Also, western and central Nebraska is located in a negative (anti-cyclonic) shear zone on the periphery of the 300mb jet streak at 12z.

At the same time, a fairly intense jet streak (60 knot maximum speed) is present at 500mb extending northeastward from central Wyoming to southwestern North Dakota (Figure 3b). The shallow shortwave noted at 300mb has an axis positioned in a northwest to southeast orientation from southeast Montana through north-central Kansas at 500mb (Figure 3b). Once again the majority of central and western Nebraska is collocated with a strong anti-cyclonic shear zone associated with the 500mb jet streak (Figure 3b).

Surface observations at 12z indicate the presence of a quasi-stationary front extending from central Nebraska southward through central Kansas (Figure 4a) (Guyer and Ewald 2004). This stationary front is characterized by a noticeable discontinuity in temperature and a very sharp change in wind direction (Figure 4a). Grand Island, Nebraska reported a due south wind and a temperature of 71°F (Fahrenheit) while 250 miles to the west Sidney, NE, reported a northwesterly wind and a temperature of 52°F (Figure 4a). The quasi-stationary front was therefore located between these two stations, but much closer to the Grand Island station (Guyer and Ewald 2004). The lack of observations across central Nebraska made pinpointing the exact location of the stationary front difficult, yet it is obvious

that it does exist at 12z by the recorded observations in Figure 4a.

The lower-tropospheric moisture convergence at 12z along the stationary front over the Great Plains is also substantial (Figure 3c). The quasi-stationary front is characterized by a fairly sharp contrast in moisture across it with surface dewpoint readings ranging from the mid 60s to low 70s to the east of the front and the mid- to low 50s to its west (Figure 4a). A strong southerly flow in the lower troposphere (900mb) out ahead of the stationary front created a region of moderately intense moisture convergence (~3-5 g/kg) along the stationary front at 12z (Figure 4a). The primary moisture transport mechanism at this time is a fairly intense southerly low level jet located over the central Great Plains which will be discussed later.

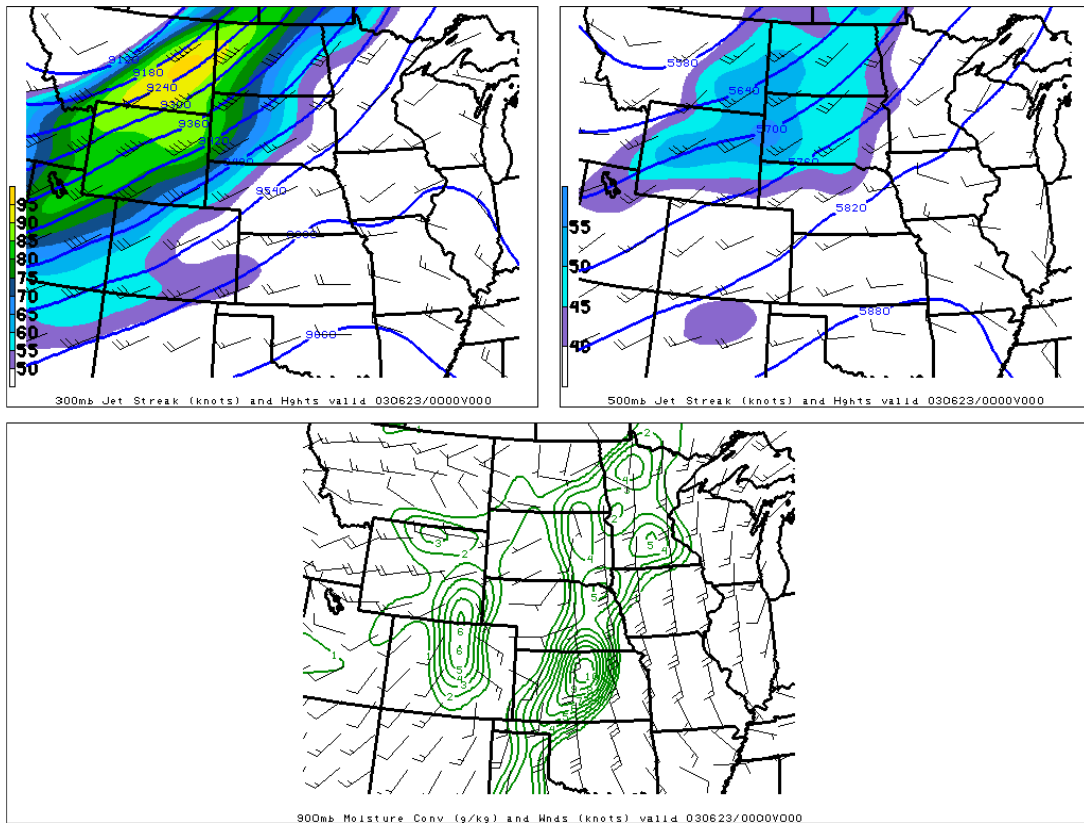


Figure 5: All plots valid at 00z 23 June 2003 with panels centered at Grand Island (GRI). (a) *upper left panel*: 300mb geopotential height (blue contours) and wind speed maximums in knots (fill) (b) *upper right panel*: 500mb geopotential height (blue contours) and wind speed maximums in knots (fill) (c) *lower center panel*: 900mb moisture convergence (g/kg) (green contours)

*b) 00z 23 June 2003*

By 00z on 23 June, the deep upper trough present at 12z was still stationed over western Montana with a fairly intense jet streak positioned along the downstream side of the trough axis (northern Utah through western North Dakota) (Figure 5a). The shallow shortwave visible in the 300mb height field at 12z, had progressed substantially eastward over far eastern Nebraska and western Iowa by 00z (Figures 3a, 5a). More so than at 12z, central Nebraska was collocated with an intense upper level (300mb) anti-cyclonic shear zone (~20 knots) at 00z 23 June (Figure 5a). At this time, the “loaded gun” sounding had been well established throughout the region and will be discussed in more detail in the following section.

The 500mb jet streak present at 12z weakened during the 12 hours that followed but remained nearly stationary (Figure 5b). Also at 00z, this mid-level jet streak appears to be more westerly than at 12z (Figure 5b). Finally, the shortwave apparent at 12z dissipated significantly between 12z and 00z and is hardly even noticeable in the 500mb geopotential height field at 00z (Figures 3b, 5b).

The quasi-stationary surface front located over central Nebraska and Kansas at 12z moved only slightly to the east between 12z and 00z (Figure 4a-c). This observation is supported by the 180° observed wind shift

from southerly to northerly between 12z June 22 and 00z June 23 at Grand Island, Nebraska (Figure 4a-c). Also, a wind shift (~60°), as well as a sharp moisture discontinuity (18°F), was reported between the observation stations of Philip, South Dakota, and Pierre, South Dakota (Figure 4c). It is therefore obvious that the quasi-stationary surface front bisects these two cities at 00z (Figure 4c).

Also by 00z, lower tropospheric (900mb) moisture convergence is much more enhanced compared to 12z out ahead (east) of the surface stationary front over central Kansas and west-central Nebraska (Figure 5c). The southerly flow out ahead of the stationary front was uniformly intense at 12z (Figure 5c). The combination of this strong southerly flux of moisture from the Gulf of Mexico, along with evapotranspiration from the thriving agriculture industry (corn) of Nebraska and Kansas, allowed for a significant increase in surface moisture (increased dewpoint temperatures) and moisture convergence along the stationary front over eastern Nebraska and central Kansas between 12z 22 June and 00z 23 June (Figures 4c, 5c, 6). A more in-depth analysis of the role of the low-level jet and other mesoscale features in the formation of supercells over western Nebraska on 22-23 June 2003 will be performed in the following section.





overnight hours. These thunderstorms eventually formed a mesoscale convective complex (MCC), with an intense low level jet over central Kansas and Nebraska transporting moisture northward as a fuel source (also not shown). These storms dumped heavy rain all across central and eastern Nebraska during the early morning hours on the 22<sup>nd</sup> before moving off into Iowa and Missouri. A sounding taken at 12z on 22 June at North Platte, Nebraska, showed a very moist boundary layer up to 850mb due mostly in part to the moisture present at the surface from the previous night's precipitation (Figure 7a). A strong

inversion had already formed at this time around 800mb with a deep elevated mixed layer (EML) aloft from 800-550mb (Figure 7a). Mixing ratio values at 900mb ranged from 14-16 g/kg over much of Nebraska (Figure 8a). At 700mb, mixing ratio values quickly dropped off to 4-6 g/kg indicative of a very dry layer aloft (Figure 8b). From the early morning hours on 22 June 2003, an ideal atmospheric setup had taken shape for the formation of supercell thunderstorms if adequate vertical wind shear and a sufficient forcing mechanism were present later in the day.

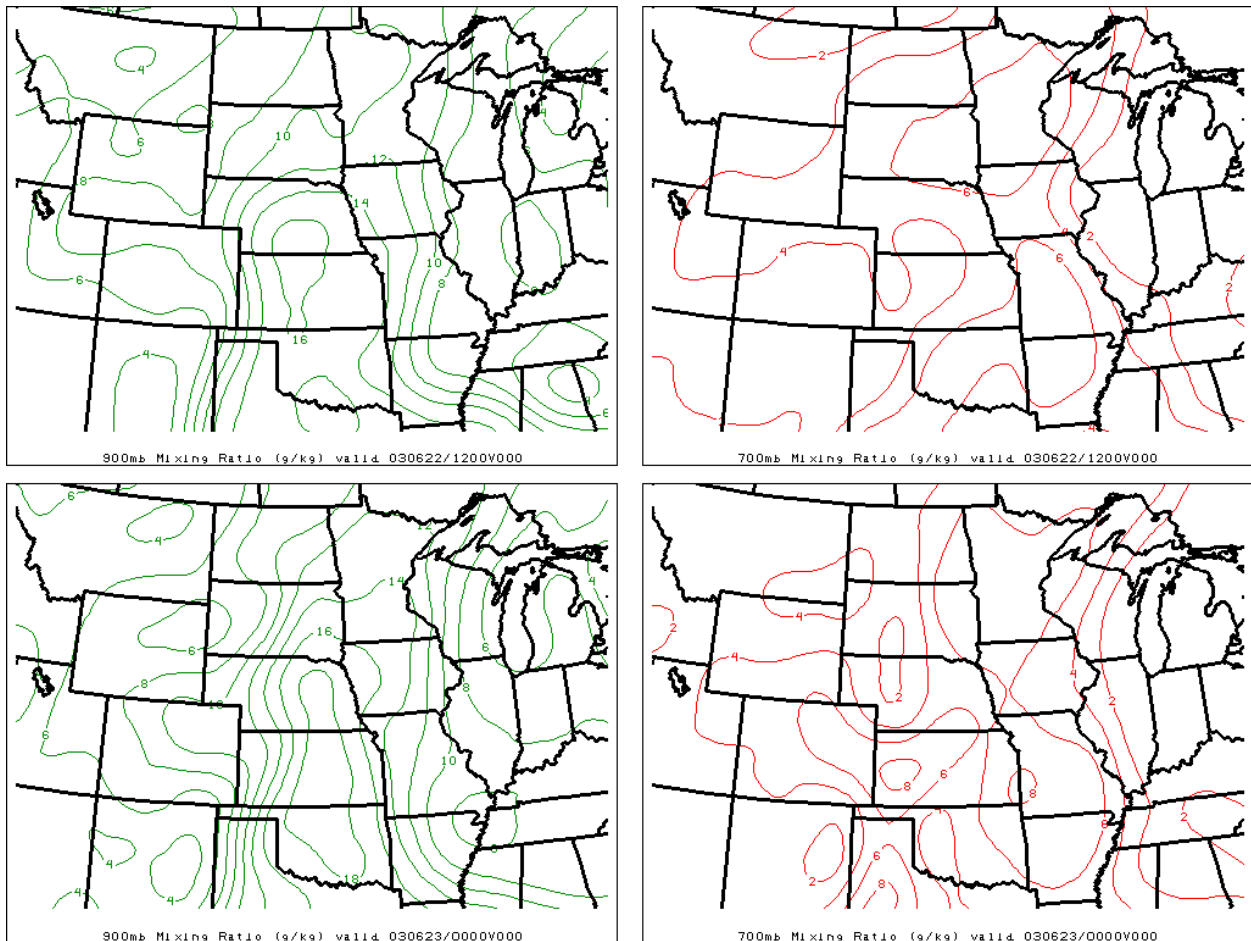


Figure 8: Top plots valid at 12z 22 June 2003 and bottom plots valid at 00z 23 June with panels centered at Grand Island (GRI). (a) upper left panel: 900mb mixing ratio (g/kg) (green contours) (b) upper right panel: 700mb mixing ratio (g/kg) (red contours) (c) lower left panel: 900mb mixing ratio (g/kg) (green contours) (d) lower right panel: 700mb mixing ratio (g/kg) (red contours)

By 00z on 23 June, an increase in daytime surface heating from 12z helped to establish a moister boundary layer from evaporation and convective overturning (Figure 7b). Surface dewpoints increased nearly 8°F across east-central Nebraska between 12z and 00z due both to the evaporation of surface moisture attributed to the prior evening's thunderstorms and also evapo-transpiration from the abundance of agricultural vegetation across the region (Figure 4c, 6). Both factors likely contributed to the increase in moisture in the boundary layer throughout the day on 22 June 2003. The surface quasi-stationary front was also visible in the 00z North Platte, NE, sounding (Figure 7b). This frontal boundary at the surface was most notably characterized by a strong vertical wind shear very close to the surface (Figure 4c). Also by 00z, mixing ratio values in the lower troposphere (900mb) increased from 12z to around 18g/kg (Figure 8c). The dry layer around 700mb was characterized by slightly lower mixing ratio values (2-6 g/kg) than at 12z on 22 June (Figures 8b, 8d). Convection fired around 2200z behind a westward propagating surface outflow boundary (OB) near Hastings, Nebraska, just east of Grand Island amidst very favorable conditions for supercell formation. These convective indices will be discussed further in the following section, preceded by a description of the OB forcing present at 00z 23 June that ultimately led to the generation of supercells that spawned numerous tornadoes and produced record hail near Aurora, NE.

#### *b) Supercell Convective Parameters*

At 12z on 22 June, significant levels of convective available potential energy (CAPE) were present over central and eastern Nebraska. Specifically, Grand

Island reported a CAPE value of 2019 J/kg at 12z and 3713 J/kg by 18z on the 22<sup>nd</sup> (Figures 7a). These levels of CAPE are very favorable for supercell formation. CAPE values in other parts of eastern Nebraska reached as high as 4605 J/kg by 00z (Guyer and Ewald 2004). There was also an extremely high level of conditional instability between the mid- and lower troposphere across the central and eastern regions of Nebraska with Lifted Indices (LI) ranging from -3 C at 12z to -5 C by 00z 23 June (Figures 7a, 7b). Around 45 knots of deep layer (0-6km) shear is evident at 00z in the North Platte sounding, which is very favorable for supercell development (Figure 7b). Large 0-3km Storm Relative Helicity (SRH) ( $247 \text{ m}^2/\text{s}^2$ ) was also present at 00z near Aurora, Nebraska (Guyer and Ewald 2004). Finally, one of the most important conditions necessary for supercell formation is a favorable balance between CAPE and vertical shear. This ratio is quantified in the Bulk Richardson Number (BRN). BRN values ideal for supercells range from 10-25. Throughout the entire day on 22 June the BRN ranged from 46-100 (Figures 7a), which is not ideal for supercells. By 00z on 23 June, the BRN dropped to near 10 at North Platte, which falls nicely into the BRN range representative of a favorable balance between CAPE and vertical shear for supercell formation (Figure 7b). Rotation was also very evident in these two cells, which is very important for hail formation. Therefore, many convective parameters that support supercell development were present across central and eastern Nebraska on 22-23 June 2003. In this case, when two different forcing mechanisms (OB and LLJ) are present under such conditions, intense thunderstorm (supercell) development resulted.

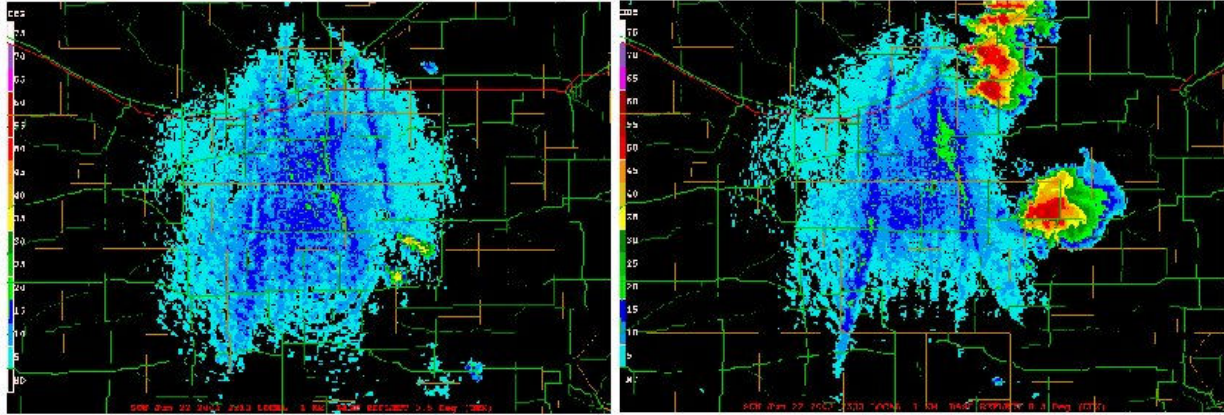


Figure 9: Radar reflectivity from the Hastings (UEX) radar site valid at (a) *left panel*: 2213z 22 June 2003 (b) *right panel*: 2333z 22 June 2003. Dark blue line of reflectivity represents the outflow boundary, which slowly moves west from panel (a) to panel (b). Convection initiated just to the east of the outflow boundary around 23z (b)

### c) *Westward Propagating Outflow Boundary*

During the early morning hours of 22 June, intense thunderstorms moved across eastern Nebraska and northeast Kansas. As they moved to the east into Iowa and Missouri by 12z, the westward propagating outflow boundary induced by these thunderstorms moved into eastern and central Nebraska (Figure 9a). By 22z, mid-afternoon, the outflow boundary was visible in the UEX radar reflectivity (most likely due to high insect concentration in the warmer moist sector of the boundary) (Figure 9a). As this outflow boundary approached the quasi-stationary front over central Nebraska and Kansas, it was forced to decelerate (Figure 9a). This ultimately led to a region of very large instability over

central Nebraska between the outflow boundary and stationary front where surface moisture steadily increased with diurnal heating and a strong southerly flow (Figure 4c). The outflow boundary therefore acted as the easternmost boundary of the high instability region, and when the low-level jet began to intensify just before 00z, convection was initiated on the cooler side of the outflow boundary (Figure 9b). Overall, the westward propagating outflow boundary induced by early morning thunderstorms played a crucial role in the localization of a strong instability axis over central Nebraska and Kansas on 22 June 2003. Combined with the low-level jet, supercells quickly erupted during the late afternoon hours over the region.

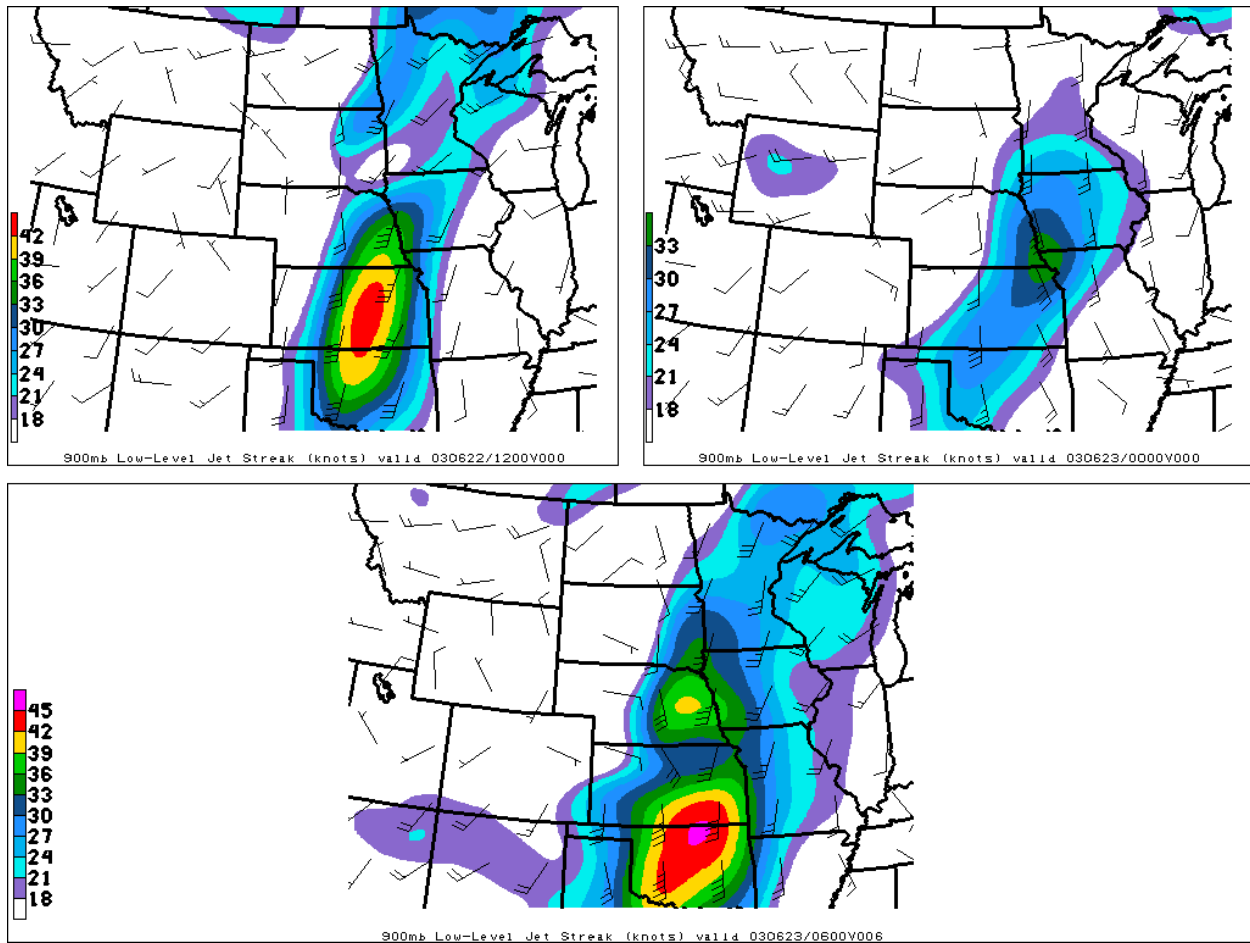


Figure 10: All panels centered at Grand Island (GRI) and have maximum 900mb wind speeds (fill) with wind barbs in knots valid at: (a) *upper left panel*: 12z 22 June 2003 (b) *upper right panel*: 00z 23 June 2003 (c) *lower center panel*: 06z 23 June 2003.

#### d) Low-Level Jet

A fairly intense southerly low-level jet (900mb) with maximum wind speeds of 40-45 knots extended from Oklahoma through eastern Nebraska early on 22 June (12z) (Figure 10a). This jet was primarily responsible for transporting very warm, moist Gulf air from the south to sustain the thunderstorm complexes that induced the westward propagating outflow boundary. This associated temperature and moisture advection acted to decrease stability and low-level convergence over eastern Nebraska aiding in vertical motion and thunderstorm sustainability. With daytime heating throughout the morning hours, this

low-level jet dissipated with increasing surface temperatures (not shown).

By 00z, the southerly low-level jet began to re-strengthen over the same region with a wind speed maximum of 33 knots at 900mb (Figure 10b). The low-level convergence at the nose of the LLJ over east-central Nebraska was precisely concentrated slightly to the east of the instability axis over central Nebraska at this time (Figures 10b and 4c). As instability near Hastings and Aurora, Nebraska increased with the approaching outflow boundary, the strengthening low-level jet acted as a forcing mechanism to break the strong cap and release the instability in the

form of isolated supercells (Figures 10b, 9b). Hence, supercells initially formed just to the east of the outflow boundary in the slightly cooler, yet moist air (Figures 9a, 9b). As the LLJ further intensified between

00z and 06z, the initial scattered supercells developed into an MCC and dropped nearly 12 inches of precipitation in areas of Thayer County, Nebraska (Figure 10c).

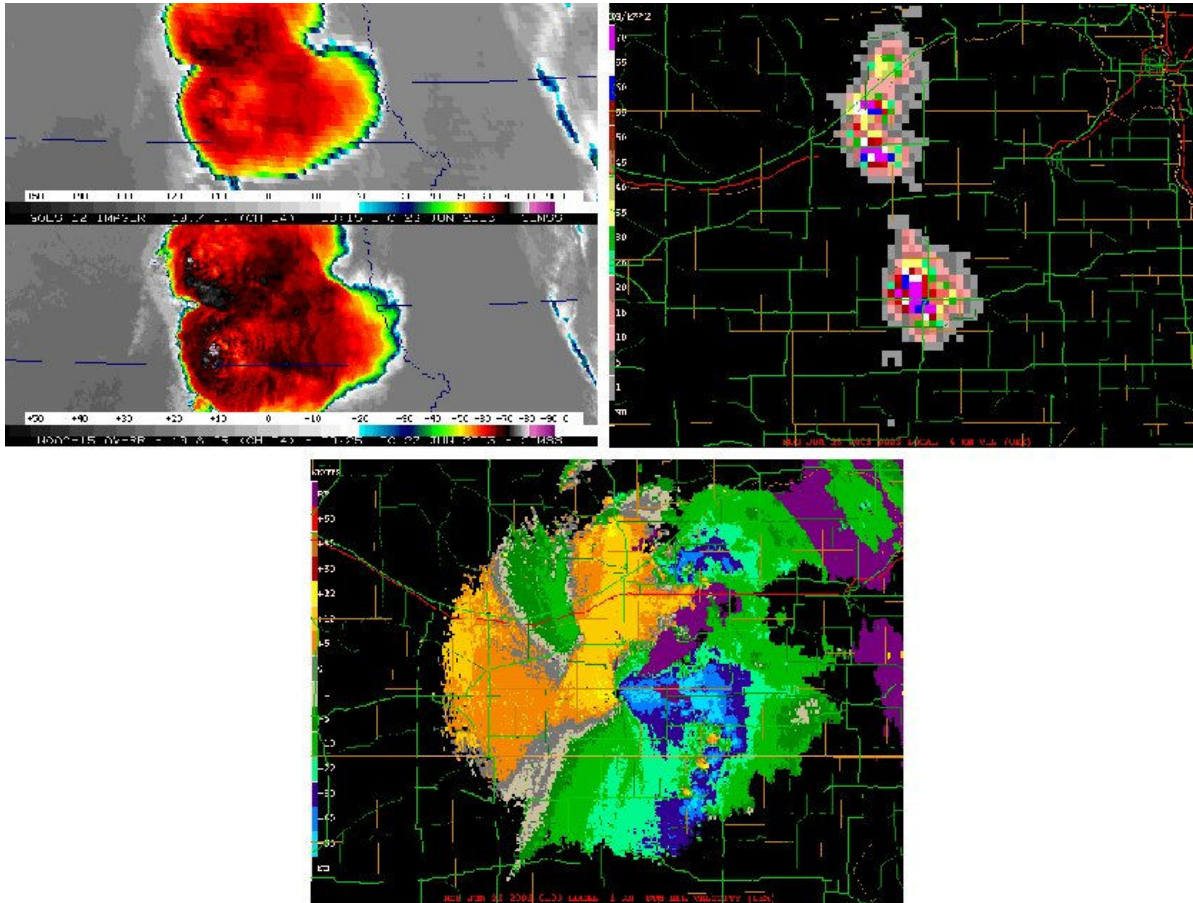


Figure 11: (a) *upper left panel*: GOES-12 satellite image valid at 0015z 23 June 2003 (10.7 $\mu$ ) (top) and 0025z 23 June 2003 (10.8 $\mu$ ) (bottom) over eastern Nebraska. Brightness temperatures are colored. (courtesy of CIMSS UW-Madison) (b) *upper right panel*: Vertically Integrated Liquid (VIL) content valid at 0003z 23 June 2003 from UEX radar site (c) Storm Relative Velocity (SRV) valid at 0103z 23 June 2003.

### e) Radar and Satellite Signatures

Figure 11a is a satellite image taken with the GOES-12 about 2 hours after the two major supercells formed on 23 June 2003. The bottom image in Figure 11a is of the 10.8 $\mu$  wavelength, ultimately measuring cloud top brightness temperatures. Two distinct overshooting tops are visible indicative of the two intense updrafts of the supercells (Figure 11a). These overshooting tops penetrate into the stratosphere, which

can be identified in Figure 11a as having brightness temperatures of -75 C to -90 C. The northernmost cell is that which produced the record hail near Aurora, NE, around 00z (Figure 11a). Very cold cloud top temperatures in both supercells, along with intense updrafts, provided for a favorable setup for hail formation. Also the enhanced-V of both supercells (shown as the nearly black brightness temperatures to the west of the brightness temperature maxima)

shows the strong stratospheric penetration of the supercell anvils with the convective outflow propagating to the west with gravity waves near the tropopause (Figure 11a).

Another radar signature used to determine favorable conditions for hail formation is a measure of the vertically integrated liquid (VIL) at a specific height of a supercell (depending on supercell location relative to the radar site) (Figure 11b). The author chose to use the Hastings, NE (UEX); radar site for all signature analyses used in this case study primarily, because of its proximity to the location of convective initiation. At 00z on 23 June, the UEX radar site recorded values of VIL as high as  $70 \text{ kg/m}^2$  (Figure 11b). This was precisely when the record 7" diameter hail was reported in Aurora. At the same time, a larger region of  $70 \text{ kg/m}^2$  VIL content was recorded near Deshler (Thayer County), NE; where widespread large hail was reported (Figure 11b). Both supercells were roughly the same distance from the radar site at 00z ( $\sim 40\text{km}$ ); and therefore, by using a radar beam with a  $0.5^\circ$  trajectory, VIL content measurements were taken at a vertical height

of 0.44 km above the radar height. Edwards and Thompson (1998) compared mean radar derived VIL contents in supercells to hail size. They concluded that in for supercells to produce  $\geq 4$ " diameter hail, the VIL content of the supercell must be  $\geq 68 \text{ kg/m}^2$ . Hence, both the Aurora and Deshler supercells were characterized a sufficient amount of liquid water for large hail to form (Figure 11b).

Approximately 1 hour after the record large hail was reported, three weak (F0-F2) tornadoes were reported near Deshler, Nebraska (Fujita 1971). These three vortices are evident in the storm relative velocity (SRV) profile at 0103z over Thayer County, NE; Republic County, KS; and Jewell County, KS (Figure 11c). This SRV reflectivity profile shows the three couplets of rotation noted by a near  $180^\circ$  of horizontal wind shear in each couplet (Figure 11c). Therefore, these three mesocyclones, which were part of the larger bow echo, were responsible for spawning weak tornadoes over southern Nebraska and northern Kansas around 01z on 23 June (Figure 11c).

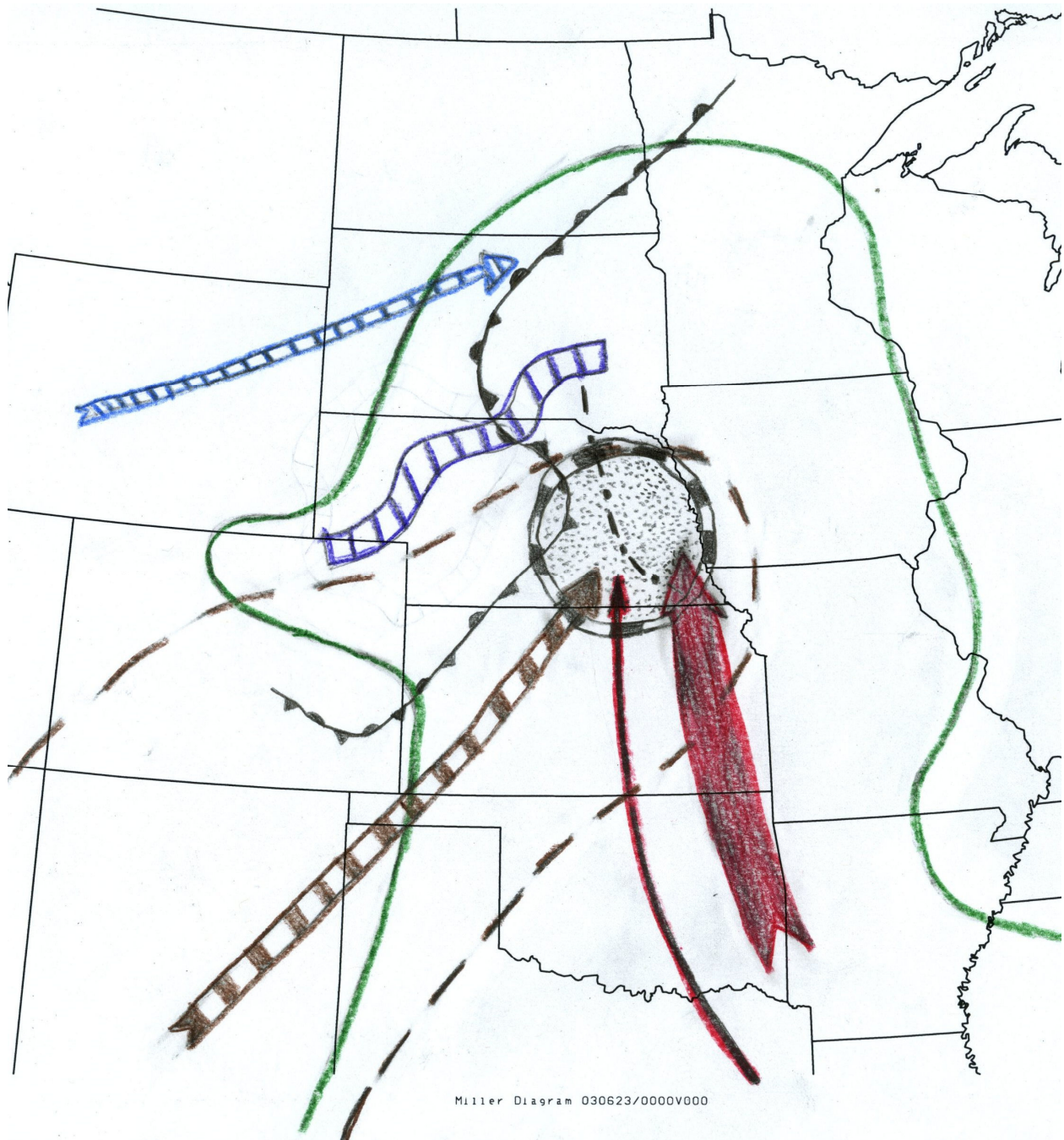


Figure 12: Miller diagram valid at 00z 23 June 2003. Analyzed features include: surface stationary front (penciled in frontal boundary, surface outflow boundary (alternating dash – dot line in graphite), 850mb moist tongue (green contour), 850mb low-level jet maximum (thick red arrow), general 850mb flow (thin red arrow), 700mb dry tongue (dashed brown line), 700mb flow (brown arrow), 500mb horizontal speed shear zone (blue divided ribbon), and 500mb jet streak (blue arrow)

#### f) Miller Diagram

Miller diagrams have been widely used in recent decades to analyze the many different synoptic and mesoscale features present in the atmospheric setup leading to a

severe weather outbreak. Figure 12 is a hand-drawn miller diagram for 00z on 23 June 2003 and displays a slightly altered synoptic type C tornado producing pattern (Miller 1972). This pattern is characterized

by a weak westerly jet at 300mb located to the north of the surface quasi-stationary front (Figure 12) (Miller 1972). The dry air intrusion at 700mb originates to the southwest and is advected over the central Great Plains by a strong southwesterly flow (Figure 12). The low-level moist tongue is advected northward from the Gulf of Mexico by both a uniform southerly flow at the surface and a strengthening low-level jet around 900mb (Figure 12). The advection into the region of this moist layer leads to an increase in potential instability; and as it overruns the quasi-stationary front and westerly outflow boundary over east-central Nebraska around 00z, this forcing leads to the development of scattered severe thunderstorms (Figure 12) (Miller 1972). This case slightly differs from the type C pattern primarily because of the westerly outflow boundary produced by the previous evenings' thunderstorms (Figure 9). As this warm moist air moves under the cooler air aloft at the stationary front, potential instability is increased (Miller 1972). At the same time, both the quasi-stationary front and the outflow boundary provide for lifting mechanisms to break the cap of the "loaded gun" profile in the region (Figure 12). Therefore, this region of initiation was near Hastings, Nebraska, shortly before 00z on 23 June (Figure 9). Miller also found that for this scenario, thunderstorms start out scattered and greatly increase in number forming a squall line once the dry air intrusion penetrates and agitates the activity zone (Miller 1972). Specifically in this case, a squall line never formed but the persistence and intensity of supercells increased once the low-level jet formed amidst the surface stationary front on the eastern periphery of the dry air intrusion at 700mb (Figure 12). This event obviously produced very large numerous hail in east-central Nebraska, which is one characteristic of the type C pattern. On the other hand,

numerous weak tornadoes were associated with the southern supercell near Deshler, Nebraska, which was not necessarily found by Miller to be a characteristic of such a type C pattern (Miller 1972).

## **Conclusion**

An initial case analysis by Guyer and Ewald (2004) contributed the supercell outbreak of 22-23 June 2003 primarily to forcing along a westward propagating outflow boundary near Aurora, Nebraska. The focus of this case study was shifted mainly toward the interaction between the outflow boundary and the strengthening of a southerly low-level jet around 00z on the 23<sup>rd</sup>. The main synoptic forcings that played into the severity of this case were intense moisture convergence to the east of the quasi-stationary surface front that was persistent throughout the day and favorable outflow conditions aloft. The intense moisture convergence is contributed mostly to moisture evaporation from the prior day's precipitation and intense evapo-transpiration from a plethora of agricultural commodities being grown in the region. As the westward propagating outflow boundary moved toward the surface stationary front during the mid-day hours of 22 June, a strong region of instability was formed over central Nebraska and reflected in the 00z loaded gun sounding at North Platte, NE. As the southerly low-level jet began to strengthen with the nose positioned over the southeastern region of Nebraska, and become aligned with the outflow boundary, convection fired just to the east of the outflow boundary. Two supercells initially formed with the northern cell dropping the record hail in Aurora and the southern cell producing many tornadoes and flooding rains near Deshler, Nebraska. Therefore, the original hypothesis was fully supported in that supercells were initiated by the interaction between the outflow boundary,



quasi-stationary surface front, and the low-level jet amidst extreme instability over central and eastern Nebraska on 22-23 June 2003.

### **Acknowledgements**

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