Precursors and Initiation of the South Dakota Tornado Outbreak of 24 June 2003

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Abstract

The severe weather of 24 June 2003 is worthy of examination due to the exceptional temporal and spatial density of tornadoes observed and confirmed in South Dakota. The event tied the record for tornadoes in a single state in a single day. An examination of the causal factors might be warranted if for no other reason than the event substantially exceeded climatological probabilities. This first in a collection of two papers investigates the precursors through initiation of this historically and scientifically significant outbreak.

Using the HYSPLIT trajectory model input with reanalysis data, the tornadogenetic air masses were traced back to their sources. The low-level parcels originated in the Ark-La-Tex region, and the mid-level parcels in the "four corners" states. Trajectory analysis enabled us to determine the speed these air parcels moved, and it was found that both parcels advected quickly, in 72 h and 24 h respectively. The same association was found with most previous large tornado outbreaks in South Dakota, and was found lacking on most other severe and non-severe weather days studied.

Pre-event awareness was somewhat hampered by the remoteness of RAOB (radiosonde observation) sites and the small number of surface reporting stations in the area, making mesoanalysis difficult. Model-derived parameters such as 0-1 km shear and 0-1 km EHI effectively sited initiation location, but forecast models seemed to underestimate the amount of moisture available for supercell and tornado generation.

1. OVERVIEW

During a six-hour period on the evening of 24 June 2003, 67 confirmed tornadoes occurred in eastern South Dakota (Fig. 1). According to the Storm Prediction Center (SPC), that number tied the United States record for most tornadoes in one state in one day (Table 1). Since the state of South Dakota averages only 25 tornadoes annually, the event was truly historic in magnitude. Most of the tornadoes were rated F-0 to F-2 on the damage scale introduced by Fujita (1971). One tornado, classified an F-4 by the National Weather Service, destroyed the small town of Manchester, injuring five people.

Before referring to single-day collections of tornadoes as outbreaks, we must ensure the event meets recognized criteria. The term tornado outbreak is not grounded in scientific principle; consideration of outbreak definitions must necessarily depend on arbitrary measures. The word outbreak may be interpreted in many different ways, by such factors as severity of tornadoes produced, numbers of tornadoes produced, proximity (spatial density) of tornadoes produced, or even how a person is personally impacted by the outcome of those tornadoes.

The American Meteorological Society glossary (Glickman, 2000) defines an outbreak as “multiple tornado occurrences associated with a particular synoptic-scale system.” In scientific literature, Pautz (1969) and Galway (1975) investigated the climatology of tornado outbreaks, defining a moderate outbreak quantitatively as consisting of ten or more tornadoes, an empirical definition that has received some acceptance in recent years. Galway settled on the number ten because those outbreaks accounted for 73% of the tornado deaths between 1952 and 1973. Curtis (2003) adopted Galway’s definition of a “large outbreak” (>20 tornadoes) in a study of tropical cyclone-produced tornado outbreaks. The example outbreaks described below easily satisfy each of those three published guidelines.

Tornado outbreaks may not only be described in terms of time and number, but also in classification of origin. In a further study of tornado climatology, Galway (1977) attempted to classify outbreaks into three distinct categories:

> Local-An outbreak in which activity is confined to a roughly circular envelope of ~$1.0\text{x}10^4$ n mi^2, with a duration rarely exceeding 7 h.
>
> Progressive-An outbreak that progresses (advances) generally from west to east with time. The distance between the first and last tornado report is normally greater than 350 n mi.
>
> Line-An outbreak with limited eastward progression that forms an axis, generally oriented north-south. The tornadoes tend to occur at widely separated locations along the line at approximately the same time.

Galway (1977) included a one-hundred year climatology of tornado outbreaks, but did not categorize those events based upon which type of outbreak occurred most frequently in each particular region of the United States.

Given the Galway definitions, the South Dakota outbreak of 24 June 2003 would fit into the classification of a local outbreak. The tornadoes occurred in the eastern half of South Dakota (mostly in the southeast quarter), roughly approximating the spatial threshold set by Galway. The duration was about one hour less than the 7 h time period referenced in Galway's climatology, satisfying that measure.

The South Dakota case was not a progressive outbreak because, although the storms generally moved west to east with time (or more specifically, southwest to northeast), the total track of the event was far less than the 648 km (350 n mi) track Galway considered. The system was also diurnal, with tornadic activity dying off in the nighttime - thus no progression, as in squall line systems, for example.

It should be noted that there is ongoing discussion in the literature about setting a standard definition of the term outbreak, possibly including criteria considering the tornado strength or damage. Edwards et al. (2004) suggested ranking the significance of tornado outbreaks giving enhanced weight to variables such as significant tornadoes and path lengths, and assigning lesser weight to non-meteorological variables such as resulting deaths. If one judges the South Dakota case in those terms, it would rank well behind many other outbreaks because the damage paths were relatively short, with none producing F-5 damage.

But as Forbes (2006) questions, why should the weight of tornadoes in an outbreak be downgraded simply because they happen to miss a community? Forbes proposes his own impact index, which ranks outbreaks based on eleven attributes including normalized tornado count, deaths and injuries, number of violent tornadoes, path length and width, damage, spatial density, and number of states affected. Based upon these criteria, the 24 June 2003 outbreak was ranked 19th among historic tornado outbreaks on Forbes' index. The South Dakota event rated high in terms of density (tornado count/duration of the event), but low in other key areas such as number of deaths and injuries, and number of significant and violent tornadoes. Damage figures were also low, partially because South Dakota (like other plains states) has a relatively low population density.

It should also be noted that numerical tornado data used to quantify outbreaks has known biases such as inflation of tornado reports in recent years, increased reporting in areas of higher population density, and better reporting from some states than others (Doswell and Burgess, 1988; Forbes and Wakimoto, 1983). Verbout et al. (2004) questions the validity of using tornado numbers for comparison purposes altogether, concluding, "any definition of an outbreak would be inherently subjective, depending upon the needs of the user."

2. COMPARISON TO PREVIOUS SINGLE-DAY OUTBREAKS

In addition to numbers and origin of tornado outbreaks, the discussion here involves tornadoes that occurred on a single calendar day. As pointed out by Schneider et al. (2004a, 2004b) in their discussion of tornado outbreak days, this qualification leads to the exclusion of some very noteworthy outbreaks in which tornadoes continued past midnight. Some events in which tornado reports extended over multiple calendar days include the "Super Outbreak" (148 tornadoes in east central U.S. on 3-4 April 1974), the November 1992 outbreak (98 tornadoes in eastern states on 21-23 November 1992), and the "Palm Sunday Outbreak" (78 tornadoes from Iowa to Ohio on 11-12 April 1965).

But when it comes to single-day outbreaks, the largest ones on record occurred in Texas, Oklahoma, and South Dakota. A review of those events yields some similarities and differences.

a. Texas – 20 September 1967

The 67 tornadoes that occurred in Texas on 20 September 1967 were generated during the landfall of Hurricane Beulah, which still holds the single-day, single state record for tornadoes from a tropical cyclone. Temporally, the Texas tornadoes were drawn out over a longer time frame than the South Dakota event. According to Storm Prediction Center (NOAA-SPC) storm reports, the Texas tornadoes began at 3 am local time and continued throughout the rest of the day, a period of approximately 21 h (although the majority did occur during daylight hours). The South Dakota tornadoes were compressed into a shorter period, starting shortly after 5 pm local time and ending just before 11 pm local time, a period of slightly less than 6 h.

Spatially, as Fig. 2 and Fig. 3 indicate, the tropical storm-induced tornadoes in Texas were far more scattered than the South Dakota event, which was compressed into a much smaller area. The Texas tornado reports occurred within a triangle-shaped area of approximately 75,000 km^2, while the South Dakota tornado paths were in a square-shaped region of approximately 26,000 km^2. (Additional tornadoes occurred on the Minnesota side of the border during the outbreak.)

The mechanisms which produced the Texas and South Dakota events are clearly different, since one was a tropical cyclone and the other a mid-latitude outbreak. But one characteristic the storm environments shared was the presence of a mid-level dry intrusion. The presence of a dry intrusion in tropical cyclone tornado outbreaks has been well-recognized. Curtis (2003) suggests a dry intrusion is present in almost all hurricane-tornado outbreaks with Atlantic and Gulf of Mexico landfalls. In Beulah's case, the significant drop in relative humidity in the RAOB (radiosonde observation) sounding from Victoria, Texas begins at approximately 900 hPa, extending throughout most of the profile (Fig. 4). The dry intrusion in the South Dakota case is evident in the 1800 UTC RAOB from nearby Omaha (OAX). A relative humidity <20% (mean dew point depression of 9°C) is noted between the 698 hPa and 566 hPa levels, 3168 m-4877 m AGL (Fig. 5).

The significance of dry intrusions in tornado production has been recognized for many years. The 700 mb dry intrusion was included by Miller (1972) in his "severe weather checklist," and specifically in what he named a Type I tornado air mass. But it is not a discriminator between tornadic and non-tornadic storms; dry intrusions are typical in warm season, mid-latitude thunderstorms (Hagemeyer, 1991).

Due to the origin of the storms, the dry intrusion was one of the few thermodynamic similarities between the Texas and South Dakota outbreaks. In both cases, the vast majority of the tornadoes were weak (≤ F-2) and relatively short-lived.

b. Oklahoma – 3 May 1999

The South Dakota outbreak is much more comparable to the outbreak in Oklahoma, because the mechanisms and environment are more synoptically similar. Both were warm season mid-latitude events, rather than the tropical landfall spin-ups in Texas. They both occurred immediately to the east of a long wave upper-level trough.

On 3 May 1999, a late afternoon and evening outbreak consisting of 68 tornadoes affected the south-central United States, in Oklahoma and Kansas (Thompson and Edwards, 2000). The most violent tornadoes occurred in the area around Oklahoma City. Of the 58 tornadoes that occurred that calendar day in the state of Oklahoma, sixteen were rated F-2 or stronger, so-called "significant" tornadoes (as defined by Grazulis, 1993). Like the South Dakota event, the tornadoes occurred in a period of less than 7 h. In both events, the strongest tornadoes also had the longest tracks (Fig. 6). The Oklahoma tornadoes were stronger, more damaging, and more lethal than the South Dakota outbreak. Forty people died, 675 were injured, over 2300 homes were destroyed, and total damage was estimated at $1.2 billion (NWS-OUN, 1999).

Upper-level dynamics appear to have played a role in both outbreaks, but with different synoptic configurations. The 1200 UTC 3 May 1999 analysis of 300 hPa pressure surface geopotential heights (Fig. 7) shows a negatively-tilted trough from Arizona northwest across the Rocky Mountains. The strongest jet maximum (≥77 m s^{-1}, or 150 kt) was approaching northern California. The same analysis on the morning of the South Dakota outbreak (1200 UTC 24 June 2003) depicts a closed low at 300 hPa over the Rockies (Fig. 8). The highest jet maximum was 60 m s^{-1} (117 kt) over Reno Nevada (RNO), although Flagstaff (FGZ) and Mercury (DRA) wind measurements at the 300 hPa mandatory level appeared to be missing. The South Dakota event, while containing greater numbers of supercell tornadoes than Oklahoma, did not have any individual storms approaching the strength of the Oklahoma outbreak - which included the powerful Moore F-5 (Burgess et. al, 2002).

c. South Dakota – 24 June 2003

The 24 June event in South Dakota was part of a widespread severe weather event throughout the upper Midwest states (Fig. 9). In the four states of Nebraska, Iowa, Minnesota and Iowa, between 6 am and midnight local standard time there were 121 reports of hail >2 cm (0.75 in), 83 damaging wind reports, and 94 tornadoes. Fourteen people were reported injured in the storms (NOAA-SPC, 2003). The tornadoes tended to be weak, with 84 of the 121 tornadoes rated F-0 or F-1. Seven were rated F-2, two were F-3, and Manchester, SD was the only F-4.

The South Dakota portion of the event began as a series of supercells (Fig. 10), then transitioned into bow echoes with strong winds, a relatively common evolution in the Northern Plains (Klimowski et al., 2004). Heavy precipitation followed, leading to five eastern South Dakota counties being placed under flash flood warnings. Subsequently, a mesoscale convective system developed in Minnesota and Iowa.

3. SYNOPTIC AND PREEXISTING MESOSCALE CONDITIONS

South Dakota's record tornado outbreak occurred on the third day of what was essentially a three-day severe weather event in the Northern Plains. A stagnant upper-level trough in the western U.S. and a very moist, unstable boundary layer over the region allowed initiation of multiple severe weather episodes from 22 June-24 June 2003. Synoptic and mesoscale features were slightly more favorable over South Dakota on 24 June than they had been on the previous two days. But as will be discussed later, convective precipitation that occurred over the region on 23 June and early on 24 June appeared to intensify those conditions.

a. Risk assessment

On 22 June, the region was rated a moderate risk for severe weather in the daily convective outlook from the Storm Prediction Center (SPC). A moderate risk designation implies the SPC expects a "greater concentration" of severe thunderstorms than with a slight risk outlook, including at least 30 reports of hail 2.5 cm (1 in) or larger, or 6-19 tornadoes, or numerous wind events (from SPC online at http://www.spc.noaa.gov/products/outlook/probinfo.html). Eastern South Dakota and eastern Nebraska were the target areas (Fig. 11).

A stationary surface front was located from central Nebraska through central South Dakota (Fig. 12), and mean layer convective available potential energy (MLCAPE; Imy, 2005) exceeding 1000 J kg^{-1}, implying moderate instability in the lowest 100 hPa AGL (defined by SPC online at http://www.spc.noaa.gov/misc/acronyms.html). But when convection developed, only five large hail reports and one wind damage report were received in South Dakota. Farther south, a U.S. record 7-inch (17.8 cm) diameter hailstone was recovered in Aurora, NE (NOAA News, 2003).

Southeastern South Dakota was once more designated a moderate risk area by the SPC on 23 June 2003, with MLCAPE again exceeding 1000 J kg^{-1} and the surface boundary remaining in place. Thunderstorms produced one tornado touchdown (Day County in northeastern SD), fifteen hail reports, and seven wind damage reports (NOAA-SPC, 2003). Just south of the South Dakota border, an F-4 tornado devastated areas around Coleridge, in northeast Nebraska, killing one person (NWS-OMA, 2003).

On the morning of 24 June 2003, the SPC placed southeastern South Dakota in a moderate risk area for the third consecutive day, along with adjoining areas of northern Nebraska. Despite two straight days of severe convection, the stationary frontal pattern allowed boundary layer moisture and convective available potential energy (CAPE; Moncrieff and Miller, 1976) to regenerate in advance of the tornado outbreak.

The only rawinsonde sounding station in eastern South Dakota is in Aberdeen (ABR). Special 1800 UTC balloon launches were ordered on all three days. While ABR is just north of the area where tornadoes occurred on 24 June, it is on the opposite side of a stationary front and is probably not a perfect representation of the air profile over the area affected. It is only close enough for a broad approximation of the state of the mid-upper troposphere in the region.

A review of selected severe weather parameters derived from the ABR soundings (Table 2) reveals that the lifted index (LI; Galway, 1956) was negative for all but one sounding during the three days preceding the South Dakota outbreak. The atmospheric column was also sufficiently moist during the period, as indicated by precipitable water values in excess of 28 mm and daytime CAPEs >2000 J kg^{-1}. The level of free convection (LFC) height was below 830 hPa during the peak heating periods approaching 0000 UTC each day. Low LFC heights imply more low-level CAPE, and increased tornadic likelihood from resulting supercells (WDTB, 2005). Additionally, the 830 hPa pressure surface is approximately 1200 m AGL, and strong support for significant supercell tornadoes occurs with LFC heights <1500 m (Davies, 2002b).

Bulk Richardson number (BRN; Weisman and Klemp, 1982), the ratio of CAPE to vertical wind shear, was a good indicator of storm type each day. Values of BRN over eastern South Dakota were high (>25) on 22 June and 23 June 2003, indicating strong buoyancy and weak shear, favoring multicells and pulse storms (Weisman and Klemp, 1984), such as those that did produce scattered hail and damaging wind reports. On 24 June, BRN was lower during the afternoon and evening, suggesting a balance between shear and buoyancy consistent with rotating updraft production.

Capping did not appear to be an insurmountable factor precluding tornado development over South Dakota on the two days preceding the 24 June event. Convective inhibition (CIN; Colby, 1983) varied greatly from sounding to sounding, a possible response to ABR being north of the stationary front that transected eastern South Dakota for three days. The 700 hPa temperature was between 5°C and 10°C, indicating a moderate cap (Davies, 2003). Even though instability was sufficient each of the three days, a convective trigger was required.

On 23 June 2003, the preferred region for severe weather was in Nebraska rather than South Dakota due to the dynamic trigger of moderate upper level vorticity. At 0000 UTC, a vorticity maximum was located in northeast Colorado (Fig. 13a). By 1200 UTC, the vorticity maximum, now +12 units of absolute vorticity ($1 \times 10^{-5}\ s^{-1}$), was collocated with its associated short wave over eastern Iowa (Fig. 13b). The most favorable condition for synoptic scale upward vertical motion is found downstream in advance of a vorticity maximum (Chaston, 1997). In this case the vorticity maximum crossed over eastern

Nebraska, where severe thunderstorms were produced.

Positive vorticity advection (PVA) increased over eastern South Dakota on 24 June 2003 due to a strong vorticity lobe upstream. At 0000 UTC 25 June 2005 (the early stages of the tornado outbreak), the 500 hPa chart (Fig. 13c) placed an elongated region of +14 units of absolute vorticity in western South Dakota, along with a high vorticity maximum of +18 units in Utah. Unlike the two previous days, on 24 June 2003 the vorticity pattern favored eastern South Dakota over areas to the south.

b. Trajectory analysis

Another explanation of why the tornado outbreak did not occur until the third day of severe weather in the Upper Midwest involves the timing of low-level moisture availability. Moisture from the Gulf of Mexico arrived in South Dakota at exactly the same time as triggering mechanisms peaked in the state.

The origin of the low-level moisture over eastern South Dakota can be determined by tracing it backward in time using trajectory analysis. The air parcel coincident to the approximate centroid of the outbreak, over Huron (KHON) at 2200 UTC, was investigated utilizing the HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model accessed through the NOAA-Air Resources Laboratory (Draxler and Rolph, 2003; Rolph, 2003). The HYSPLIT model is generally used for air quality situations involving transport, dispersion, and deposition. In this case, NCEP/NCAR reanalysis data (Kistler et al, 1996) was fed into the model to trace the parcel over KHON back to its source 72 h earlier (Fig. 14).

This is similar to the approach used by Cheresnick and Basara (2005) to trace moisture advection preceding a 2001 tornado in Benson, MN. Brimelow and Reuter (2005) also used this approach to assess low-level moisture transport from the Gulf of Mexico to high-precipitation events in Canada.

The source region of the parcel 72 h prior to the outbreak was near Fort Polk, Louisiana. It possessed the characteristics of maritime tropical (mT) air. The original surface temperature was 31°C (88°F), with a dew point of 23°C (75°F). The "tongue" of moisture demonstrated by high dew points and predominance of southerly surface winds suggested a conveyor belt was already established on the eastern side of the trough over the Great Basin (Fig. 15). The trajectory of the parcel carried it northward through eastern Oklahoma, eastern Kansas, and eastern Nebraska before reaching eastern South Dakota. The movement roughly approximated the warm sector of the convective storms that erupted in the Central Plains.

Vertical ascent of the parcel was minimal, as it remained in the lower boundary layer the entire period from source to destination. The parcel did not even reach an altitude of 500 meters AGL until it arrived in Huron, and that upward movement was probably a local response to the strengthening, nearby surface low. The moisture convergence over eastern South Dakota greatly increased the surface-based CAPE values over eastern South Dakota, promoting the development of supercells on 24 June 2003.

c. Trajectory comparison with previous South Dakota outbreaks

In examining whether this was a typical setup for tornado outbreaks in South Dakota, it is useful to examine the air parcels present during previous events. The link between mT air from the Gulf region and eventual precipitation and convective events in the northern US is widely accepted. Hagemeyer (1991) compiled an extensive lower-trospospheric thermodynamic climatology, concluding the Gulf of Mexico was the primary source region for surface moist air masses in the Upper Midwest during the summertime (Fig. 16). But the relationship between between the Gulf and tornado outbreaks in South Dakota has not been established, so we endeavored to determine if one exists.

A listing of previous same day, multiple-tornado events was assembled. A composite map of previous tornado reports and paths in the state from 1950-2003 (Fig. 17) reveals a significant bias toward the more populated, eastern side of South Dakota. It is conceivable that there may be fewer tornadoes in the western half of the state than the east due to more arid conditions west of the Missouri River. But numerous national studies have shown tornado reports to be heavily weighted toward population centers (Anderson et al., 2005), and there is no reason to expect the tornado record in South Dakota to be any different, with a higher population density in the eastern half of the state.

Nevertheless, a review of recognized archives of tornado reports (Grazulis, 1993; NCDC, 2006) would provide an approximation of previous multiple tornado days that have occurred in the state for the purposes of comparing source regions of tornadogenetic air parcels.

Using a combination of the Grazulis and NCDC reports, a listing of large South Dakota outbreaks from 1950-2005 was compiled. It should be noted after a review of the data that in some instances, a tornado registered a second tornado report simply by crossing a political boundary into another county. Some errors were also detected, and an attempt was made to verify and complete the record by reconciling Grazulis and NCDC. The field of South Dakota outbreaks was trimmed to calendar days in which 13 or more tornadoes occurred, resulting in the 11 largest outbreaks on record (Table 3).

The collection of 67 tornado reports from 24 June 2003 is due, in part, to the abundance of storm chasers and video recordings of the tornadoes, and a thorough post-event damage survey conducted on the ground and in the air by the NWS. Given the scope of those efforts, it may not be a surprise that no previous tornado day generated even half as many confirmed tornadoes in South Dakota as 24 June 2003.

1) Low-level parcel trajectories

The date and time of the first tornado report in each of the outbreaks, along with a subjective estimation of the centroid of the associated damage paths, were input into the HYSPLIT model as endpoints. In each case, we also positioned each endpoint at a vertical height of 500 m AGL to represent the low-tropospheric environment, because an endpoint closer to the surface would risk a parcel trajectory "collision" with the ground due to terrain variations. With vertical velocities obtained from the omega fields in the reanalysis data, the model then calculated a backward trajectory to the origin of the air parcel involved in each of the outbreaks. During that process, it was found that even slight input changes of the location or time of the ending point of the backward trajectory sometimes yielded significant differences in parcel origin. In an attempt to ensure the trajectory was representative of the tornadic environment, trajectory ensembles were also examined. The HYSPLIT ensemble routine involved perturbing the meteorological data at the end point (the centroid of tornado reports) by one grid point horizontally and 0.01 sigma level (±250 m) vertically (Draxler, 2003). The reanalysis data has a horizontal resolution T62 (truncated to 62 waves), plotted in grid boxes 2.5 deg latitude x 2.5 deg longitude (Kistler et al., 2001). Over South Dakota, these grid boxes are approximately 275 km latitudinally and 200 km longitudinally. There were 27 ensemble trajectories generated for each case studied.

The ensembles showing the Ark-La-Tex (Arkansas-Louisiana-Texas) connection to the 24 June 2003 tornadoes were consistent (refer back to Fig. 14, inset). All but seven of the 27 ensemble trajectories showed a 72 h parcel origin in the Ark-La-Tex region or adjacent waters of the Gulf of Mexico.

The second highest number of single day tornadoes in South Dakota occurred on 7 June 1993, when 28 tornadoes occurred in the southeast quarter of the state. Similar to the 24 June 2003 event, this parcel originated (Fig 18a) near the Texas-Louisiana border, and advected to South Dakota in 72 h. The parcel involved in the 11 May 1985 event (Fig. 18b) also originated near the Texas-Louisiana border, and although it was a bit displaced to the west, it again reached South Dakota in 72 h, where it was involved in 20 tornadoes in the southeastern part of the state.

Further examination reveals that, in addition to the 24 June 2003 outbreak, the Ark-La-Tex region was the parcel source of six of the next nine largest tornado days in South Dakota: the 24 June 2003 and 11 May 1995 events previously mentioned, the 16 June 1992 event (Fig.

18c), the 24 May 1965 event (Fig 18d), the 29 May 1980 event (Fig. 18e), and the 19 June 1979 event (Fig. 18f). In each of these events the parcel advected to South Dakota quickly, within 72 h. (Reanalysis data from the 8 May 1965 tornado day was disregarded due to errors.)

Analysis of the remaining three events shows that not all South Dakota multiple tornado days are preceded by swift advection of air from the Ark-La-Tex. The source parcel of the 6 July 1987 event was in southern Kansas three days out (Fig. 18g), and central Nebraska two days out, suggesting - although there was significant ensemble disagreement - a rather neutral advection pattern leading up to the 14 tornadoes that resulted in central South Dakota. Widespread rains occurred in advance of the tornadoes, which occurred after daytime temperatures in the upper 80s°F (approx. 30°C).

There were two other outlier cases. The low-level parcel from the 4 June 1980 event (Fig. 18h) originated in Texas, but it was the exception among the ensembles, among which there was wide deviation. The 28 May 2004 (0000 UTC 29 May, Fig. 18i) parcel appears to come from the west, although it did assume the more usual south to north advective paths in the final 24 h. The ensembles from 24 May 2004 are inconsistent until the final 24 h, when they pass through eastern Nebraska, moving north coincident with a low level jet of 23 m s^{-1} (45 kt) at 850 hPa.

Another issue for research may be the Ark-La-Tex connection to South Dakota tornado outbreaks, particularly those outbreaks that occur in the eastern part of South Dakota. Researchers have determined, for example, that a link exists between rainfall trends over the

Midwest and the 850 hPa moisture fetch originating in the Gulf region. Expressed as the Reiman index,

$$RI = 850V_g = \frac{g}{f}\ \frac{Zeast - Zwest}{(\text{distance between } Zeast \text{ and } Zwest)},$$

in which *g* is the gravitational acceleration, f is the Coriolis force, and the Z terms are the geopotential heights at 850 hPa (Miller and Taylor, 2004). Essentially, it is an expression of the geostrophic wind component (the *v* component) northward from a part of the country that is normally moisture rich due to its proximity to the Gulf of Mexico.

Perhaps there is a similar link to tornado events in South Dakota, given that the suspect regions of origin are approximately similar. It is unknown if improved tornado outbreak predictability could result, especially since (as demonstrated by the Reiman Index) a Gulf moisture fetch is also a favored component for rainfall and other types of precipitation events.

Some similarities and some differences are obvious when comparing 24 June 2003 to previous significant tornado days in South Dakota. While there is no apparent trajectory pattern match between all of the events, the 24 June 2003 does have boundary layer source similarities to a majority of the previous large tornado days in South Dakota, which occur in low-level air that most often originated in the Ark-La-Tex region 72 h prior to the outbreak.

2) MID-LEVEL PARCEL TRAJECTORIES

Low-level moisture is only one ingredient involved in tornado outbreaks. As previously discussed in this paper, mid-level intrusions of dry air are also a contributing factor. Lemon (1998) suggests the dry intrusion helps amplify mesocyclones, many producing strong or violent tornadoes. We ran the HYSPLIT model again, testing the mid-level air parcels involved in the largest tornado outbreaks in South Dakota to determine their source regions.

During this process it was important to choose a proper elevation of the mid-level end point. Hagemeyer (1991) suggested that since potential wet-bulb temperature ($\theta\omega$) is conservative to moist and dry adiabatic processes, as well as evaporation from rainfall, it is a good indicator of dry locations in the troposphere. Since the climatological minimums of $\theta\omega$ are found at ~750 hPa, he used that as an average representation of the dry layer. We chose 2500 m AGL to approximate that level over South Dakota. We again ran ensembles, so endpoint parcels from 2250 m AGL-2750 m AGL were also included in the sample. Because the winds of greater velocity would be expected at that level, we only ran the trajectory back 24 h, rather than the 72 h we looked at with the low level moist parcels.

The results (Fig. 19) show that 24 h previous to the outbreaks - with good ensemble agreement - the parcels from seven of the ten events studied originated in the "four corner" states – Utah, Colorado, Arizona, and New Mexico. The outlier events were 24 May 1965, in which the parcels originated in East Texas; and 6 July 1987 and 28 May 2004, when the parcels originated in Wyoming. The result that 24 h prior to 70% of the tornado outbreaks, the 2500 m AGL parcels were southwest of the tornado region in South Dakota is to be expected because, as previously mentioned, western troughs are often in place and would add a southwesterly component to the winds flowing into the tornadic region. There are at least two other implications:

1) During the summertime, the four corners area is dominated by dry, continental tropical (cT) air originating on the Mexican plateau (Ackerman and Knox, 2003). Trajectories indicate that dry air is then transported into South Dakota. Because this occurs coincident with mT air arriving from the south, the differential advection of contrasting air masses is established. Differential advection is often associated with tornado occurrence (Appleby, 1954).

2) The horizontal transport of these parcels in *every* case examined is well to the left (west) of the collocated low-level moist parcels studied earlier. This implies a veering with height of the environmental winds, generally from the south in the moist parcel with an endpoint of 500 m AGL at the endpoint tornado location, and generally from the west or southwest at the 2400 m AGL endpoint. Even in these broad scale trajectories, directional shear is generated.

3) COMPARISON WITH NON-TORNADIC OUTBREAKS

While we see that in most cases, low-level moist parcels were advected from the Ark-La-Tex region 72 h before South Dakota's largest tornado outbreaks, and dry mid-level parcels advect from the four corners states 24 h before, there is no predictive value if this same parcel relationship occurs on days which produce few tornadoes – or no tornadoes at all. We therefore examined backward trajectories on days which produced fewer numbers of tornadoes, as well as hail and damaging wind reports in South Dakota. This would indicate if

HYSPLIT trajectory source origins could be used as a discriminator between tornadic and non-tornadic severe weather outbreaks, such as occurrences of large hail and damaging wind.

In order to filter out days with only isolated severe weather events, we used a list of "organized severe thunderstorm episodes" compiled during 2003 by the SPC and NSSL (Crisp, 2007). (Criteria for what qualifies as an organized episode is available online at http://www.spc.noaa.gov/exper/archive/events/index-abs.html [accessed 2007].) From those we selected the 35 episode dates in which storm reports were generated in South Dakota (Table 4). The data consists of the preliminary storm reports, so additional storm damage may have occurred and later added to the official storm reports. We chose the event start as the date and time of the first tornado report in South Dakota, or the first hail report if no tornadoes occurred.

We found through backward trajectories that very few (five of 35) had a parcel source origin in the Ark-La-Tex region ≤72 h prior to the event. Only the 24 June tornado outbreak central to this paper had such an origin, along with the two preceding severe weather days, 22 June and 23 June (Fig. 20). There were two other 2003 cases with a Texas parcel origin: 8 July and 14 July, on which one tornado and zero tornadoes occurred, respectively (Fig. 21).

We then examined those cases to see if there was a coincident mid-level dry parcel originating in the four corner states, similar to the large tornado outbreak days in South Dakota. In the two days prior to the 24 June outbreak, the preponderance of ensemble parcels did originate from the southwest 24 h previous to the event (Fig. 22). But on the two July severe weather days, the 2500 m AGL ensemble parcels originated farther to the west in Nevada and Wyoming - not from the southwest direction of the four corner states.

3) COMPARISON WITH NULL CASES

After identifying the differential advection involved in tornado outbreaks and severe weather outbreaks, we then studied null cases. Since we are examining warm season air masses, we looked at air mass trajectories for remainder of days between 1 May and 30 August 2003 in which there was neither a tornado outbreak nor severe weather episode. Since most days did not have official storm reports to use as a trajectory end points, we used Pierre (KPIR), the approximate geographical center of South Dakota. For a timeframe, 0000 UTC was chosen for each of those days because it appears a reasonable approximation for the period prior to sunset which is the diurnal maximum for temperatures and non-tornadic severe thunderstorms in the US (Kelly et. al, 1985).

The HYSPLIT trajectories were run for each of the 87 days in which there were no severe weather episodes affecting South Dakota (Fig. 23). The endpoints were set at vertical heights of both 500 m and 2500 m for reasons previously discussed. Each of the dates was examined to see if they contained a preponderance of ensembles in which the parcel at 500 m AGL originated in the Ark-La-Tex 72 h previous *and* 2500 m AGL parcel origination in a four corners state 24 h previous. From the 87 dates, four were judged to warrant further consideration based upon the ensembles: August 16, August 17, August 19, and August 22.

A closer examination of those dates shows there were significant ensemble differences, and the actual trajectory paths (Fig. 24) do not match tornadogenetic parcels observed in the outbreaks. On 16 August, the 500 m AGL parcel originated in Texas, but the 2500 m came from Kansas (although it is certainly close to the Colorado border). On 17 August, the 2500 m AGL parcel came from the four corners state of Colorado, but the low-level parcel came from far west Texas, which is not normally considered the Ark-La-Tex region. The 19 August and 22 August 500 m parcels originated nowhere near the Ark-La-Tex. We conclude there is no correlation between the parcel trajectories of non-severe episode days in the warm season and the parcel trajectory origins that were present in the South Dakota tornado outbreaks studied in this paper.

In summary, we determined that the majority of the largest tornado outbreaks had swift advection of low-level air parcels from the Ark-La-Tex, coincident with a 24 h advection of dry air in the mid-levels from the four corner states. These two factors were present in only the three day severe outbreak from 22-24 June (which included the record tornado day), but no other severe weather episodes affecting South Dakota in 2003. We conclude the likelihood of a tornado outbreak is significantly higher when the rapid differential advection of air parcels from the south and southwest takes place, since that is what happened in 70% of the largest tornado days in South Dakota history.

The advantage of trajectory analysis over merely analyzing winds and air mass movement on mandatory level constant pressure charts is that trajectory models provide the velocity of the parcel advection, account for model-based vertical velocities, and locate the parcel movement with greater accuracy through numerical calculations. One factor which might inhibit the use of these parcel trajectories operationally in tornado outbreak prediction is that a backward trajectory is not always the same as a forward trajectory. In other words, to run the model not from endpoint to origin does not always yield the same result as running it from origin to endpoint during the same time frame. In this case, the backward and forward trajectories do give identical results, possibly because of the way the reanalysis archive is modeled. We started a parcel in western Louisiana at 36 m AGL three days before the SD tornado outbreak, and ran the trajectory forward 72 hours. It arrived in eastern South Dakota at the same tornadogenetic endpoint we used for the backward trajectory (Fig. 25). But this is not always the case, due to the accumulation of numerical error (up to 5% per day) inherent in HYSPLIT trajectory analysis (Draxler and Rolph, 2003).

d. Upper air features

On the day of the 24 June 2003 outbreak, the upper level flow featured a highly-amplified western trough, providing a strong southwest upper-level flow into the Northern Plains. The resulting divergence on the northeast side of the trough resulted in broad-scale vertical motion over the region. (Western troughs were also present in the ten previous South Dakota outbreaks just described, though in most cases the troughs were not as amplified as the trough on 24 June 2003.) The 300 hPa analysis from 1200 UTC (Fig. 26) depicted a large area of winds in excess of 36 m s^{-1} (70 kt) through the active region of the trough into western South Dakota. A jet maximum exceeding 51 m s^{-1} (100 kt) exited the trough axis in southern

Utah (as depicted by the shaded area in Fig. 26). Diffluent flow is observed downstream in North Dakota and northern Minnesota.

Just before the onset of afternoon convection in South Dakota, the Rapid Update Cycle (RUC; Benjamin et al., 1994, 2001) indicated a broad area of 26 m s^{-1} (50 kt) flow at 500 hPa from central into northeastern South Dakota (Fig. 27), paralleling an existing surface boundary. An embedded area of 31 m s^{-1} (60 kt) southwest wind was also identified in the central part of the state. Such winds would be indicative of a jet streak, influencing development of an extratropical cyclone and surface low-pressure system (Rauber et. al, 2005).

e. Surface observations

The emergence of the surface features can be analyzed by plotting the METAR reports from the network of surface observation stations. Unfortunately, such networks seldom have the density of reporting points meteorological researchers would desire. That is the case in this instance, as the number and geographic spacing of stations hindered the precision of the surface analysis.

In particular, there is a paucity of reporting stations in northern Nebraska, a region of cyclogenesis for the 24 June 2003 outbreak (Fig. 28). It should be noted that the KTIF sensor at the Thedford-Thomas County Airport did not exist in 2003, so the data void in north central Nebraska was even more significant at the time. While the High Plains Regional Climate Center operates an automated weather station in Halsey, 27 km (17 mi) southeast of Thedford, its hourly observations do not include barometric pressure (Sandra

Jones, personal communication). The data void in that sparsely-populated region is so acute it is even difficult for the state climatologist to maintain climate reports (Al Dutcher, personal communication). According to US Census Bureau data, the area has a population density <10 persons per square mile (2.6 km^2).

Based on a subjective analysis of the surface observations available, a surface low developed in western or southwestern Nebraska during the morning of 24 June. The placement of the low at 1500 UTC (Fig 29) is questionable, based on whether one uses the pressure field or wind and temperature/dew point fields. The actual center of low pressure is near the Kansas border, but there was at least one reporting station (KOGA) northwest of that on the southern edge of the panhandle with a south wind, temperature of 25°C (77°F), and a dew point of 17°C (63°F). In any case, a surface warm front bisected Nebraska from west to east, separating dew point temperatures of 21-23°C (70-73°F) in eastern Nebraska from dew points of 17-19°C (62-67°F) in eastern South Dakota, where surface pressure began to fall. Winds in central South Dakota backed to the northeast by 1700 UTC (Fig. 30) and the warm front reached into southeast South Dakota, producing a temperature of 27°C (81°F) in Yankton with a dew point of 22°C (72°F) despite three-quarter cloud cover. By 1900 UTC (Fig. 31), the sea-level pressure in Mitchell had fallen to 1006.3 hPa. As cloud cover decreased, the Mitchell temperature also rose and dew point increased to 22°C (72°F). At this point, the SPC issued a tornado watch.

The warm front continued to surge to the north and the barometer continued to fall in Mitchell, to 1004.6 hPa at 2100 UTC (Fig. 32). The warm front was now aligned southwest to northeast along the mean 850 hPa flow, and would remain generally stationary in such an alignment for the next three hours. At 2300 UTC (Fig. 33), the pressure in Mitchell had dropped to 1003.4 hPa with thunderstorms, one of which strengthened into the first supercell of the outbreak.

For forecasters trying to anticipate the initiation of this event, the lack of data around Thedford was problematic. Judging by the veering wind pattern, the center of the low was probably closer to Thedford, rather than the plotted surface pressure minimums farther south. Placement of this feature would become crucial to those chasing and tracking supercell development. The strongest tornadoes would form along the stationary/warm front, while the weaker tornadoes would occur in the warm sector ahead of the slowly advancing cold front. The stronger tornadoes also occurred within 100 km of the plotted surface low, and on the northeast side, in the vicinity of the warm front. Historically, most tornadoes F-2 or greater in the Dakotas (58%) occur north of the surface low along an inverted trough (Guerrero et al., 1998; Johns et al., 2000). Only 8% of the tornadoes ≥F-2 in the Guerrero study occurred northeast of the low along a warm or stationary front. In the 24 June 2003 event, while the strongest tornadoes were northeast of the low, the greatest number and weakest tornadoes occurred east or southeast of the low in the warm sector. The northeast quadrant is the favored location in Broyles et al. (2002), which revealed that most tornadoes ≥F-3 in the Northern Plains occurred east of the surface low.

Analyses of initial conditions from the RUC can help fill in gaps in actual observations. RUC incorporates an analysis and an assimilation system to modify forecast fields in a high-resolution grid for high-frequency, short-range model forecasts. At the surface (Fig. 34), a trough of low pressure stretched from central Nebraska through southeastern South Dakota and then as a stationary/warm front into southwest Minnesota. A RUC-analyzed surface low was placed just north of the South Dakota/Nebraska border. Behind the associated warm front MLCAPE was in excess of 3000 J kg^{-1}.

Surface dew points of 24-26°C (70-77°F) were widespread in eastern South Dakota. It is possible that the low-level moisture pool was reinforced by advection from the south. The night before the event, heavy rains occurred in northeast Nebraska with NWS flash flood warnings issued. Southerly winds blowing over wet ground probably helped increase surface dew points in South Dakota in the hours preceding the tornadic event.

f. Special sounding parameters

The special 1800 UTC balloon sounding from OAX (Omaha NE, Fig. 35) indicated CAPE of 3276 J kg^{-1} and a LI of -8. The winds veered from southeast at the surface to southwest at 26 m s^{-1} (50 kt) at 500 hPa. Abundant moisture was available, with 42 mm of precipitable water. Because of the associated potential for heavy rain, flood watches were posted in addition to the tornado watches that were issued for eastern South Dakota. The special sounding also revealed a low lifting condensation level (LCL 878 hPa, approximately 1180 m AGL) and low level of free convection (LFC 857 hPa, approximately 1399 m AGL). Such low heights enhance the potential for low-level mesocyclones (Rasmussen, 2003). In addition, the relatively small height difference between the two values indicated that deep convection was more likely (Thompson, 2003).

A layer of mid-level dry air was also indicated between the 700 hPa and 500 hPa levels, further supporting vertical ascent. The capping inversion weakened considerably from south to north across the region. The 1800 UTC sounding temperature at 700 hPa was 10.8°C at OAX, but only 7°C at ABR (Aberdeen SD) – although the apparent difference may actually have been influenced by the surface front located between the sounding points.

The value of the energy-helicity index (EHI; Hart and Korotky, 1991) combining CAPE and helicity for a measure of tornado potential (more specifically, the ability to tilt horizontal vorticity into thunderstorms) has been evaluated by several researchers, including Davies (1993). More recent research finds a particular value in EHI computed for the lowest one kilometer useful for discriminating between tornadic and non-tornadic supercells (Rasmussen, 2003) and between non-tornadic and significant tornado supercells (Edwards, 2000).

Based upon this EHI_{0-1} research, we would have correctly expected tornadic supercells during the South Dakota event. EHI_{0-1} values derived from the 2200 RUC (Fig. 36) indicated a maximum just west of Mitchell, coincident with the surface low and almost exactly where the first tornadic supercell formed. Similarly high values were indicated over the area throughout the evening as additional tornadoes formed, particularly those near the surface front.

g. BUFKIT analysis

Since Mitchell is approximately 200 km from the RAOB location in Aberdeen and 320 km from the Omaha-Valley RAOB, a model-based virtual sounding is potentially more representative of the atmospheric profile. The 1800 UTC run of the meso-Eta model grid was examined over Mitchell using the analysis program BUFKIT (Mahoney and Niziol, 2000).

At 2100 UTC, immediately before storm initiation, the BUFKIT sounding depicted a highly unstable atmosphere with high CAPE (3769 J kg^{-1}) and significant shear (Fig. 37). The LCL and LFC were nearly coincident at approx 840 hPa, or just over 1 km AGL. Winds veered from southeast at 19 kt (9.7 m s^{-1}) at the surface, to southwest at 39 kt (20 m s^{-1}) at 500 hPa . These conditions resulted in an "H3" classification in the Convective Storm Matrix (COMET, 1996) suggesting strong, dominant, right-moving supercells.

Meso-Eta forecast shear correctly anticipated the strongest cells. In recent years, a key discriminating factor that has emerged between cells that produce significant tornadoes and those that do not is 0-1 km shear (Markowski et al., 2002). Craven et al. (2002) reports strong low-level shear is associated with a higher frequency of tornado events, with a distinct lower-bound of 10 m s^{-1} of shear in the lowest kilometer for significant tornado producers. In BUFKIT, mean shear is defined as the length of the hodograph divided by the depth (in this case, 1 km) being measured (WDTB, 2005). A hodograph examination of 1800 UTC Eta forecast virtual sounding over Huron showed a 0-1 km shear of only 5 m s^{-1} at 2300 UTC (Fig. 38a). Within a 2 h period, the forecast backed the surface winds to the east as the surface low approached, and increased the 1 km winds to 13.9 m s^{-1} (27 kt), resulting in a 0-1 km shear of 14 m s^{-1} at 0100 UTC (Fig. 38b). That was approximately the time of the right-moving supercell that produced the nearby Woonsocket F-3 and Manchester F-4 tornadoes, and the shear value was now above the 0-1 km threshold detailed in Craven's climatology.

h. Storm relative winds

Another model-based wind parameter can also be investigated in the context of tornado anticipation. Eta model derived storm relative winds appear to be an effective discriminator between tornadic and non-tornadic supercells. A study published by Thompson (1998) concludes that "test results of storm relative wind speed at the Eta model surface level and at 500 hPa, derived from gridded Eta forecast fields, demonstrate skill in distinguishing tornadic and non-tornadic supercells in daily forecast operations at the Storm Prediction Center."

Storm relative wind flow is important for sustaining the inflow-outflow balance within the supercell. If the mid-level flow is too strong, precipitation will be carried away from the updraft region of the supercell, inhibiting rain-cooled outflow. If mid-level flow is too weak, precipitation will wrap around the mesocyclone, effectively "undercutting" the thunderstorm (Davies-Jones et al., 2001). When comparing the Eta forecasts preceding tornadic and non-tornadic cases, Thompson discovered a climatological lower-bound of 8 m s^{-1} storm relative wind at 500 hPa (approximately 5000 m AGL) in storms that produced tornadoes. Non-tornadic thunderstorms often occurred in storm relative 500 hPa wind forecasts below that 8 m s^{-1} threshold.

An examination of the Eta 12 h forecast (Fig. 39) and 24 h forecast (Fig. 40) valid at 0000 UTC 25 June 2003 shows them to be relatively consistent regarding the mid-level wind flow. At the 5000 m level, approximating the 500 hPa pressure level investigated by Thompson, the forecasts were similar. The Eta forecast for the tornadic region was for a southwest storm relative wind at ~10.3 m s^{-1} (20 kt) on both runs.

In this case, the Eta mid-level storm relative wind test survives the lower bound. Interestingly, the storm relative wind forecast was 2.5-5.0 m s^{-1} (5-10 kt) slower in Minnesota, which was not experiencing tornadoes during this time period. Western South Dakota did have storm relative mid-level winds of 10 m s^{-1} (20 kt), but that was on the colder, less tornado-favored side of the surface boundary.

4. NEAR-STORM ENVIRONMENT

The significance of boundary layer convergence zones in generating convection has been recognized for many years. A relationship between such boundary layer zones and convective initiation has been demonstrated in studies such as Wilson and Schreiber (1986) in Colorado, and Koch and Ray (1997) in North Carolina. Markowski et al. (1998) concluded nearly 70 percent of the significant tornadoes occurring during the VORTEX-95 project were located near low-level boundaries unrelated to supercell downdrafts. Similarly, during the South Dakota event studied here, numerous low-level boundaries were in place in areas in which convection developed and tornadoes occurred.

During the night and morning preceding the event, there was widespread rainfall in northeast Nebraska, western Iowa, and eastern South Dakota. Nearly all of the area received measurable rainfall. Some parts of the area received unusually heavy rains (Fig. 41), and those rains may have contributed to the boundary layer conditions that helped initiate supercells later in the day. Johns et al. (2000) suggest that evapotranspiration often plays a significant role in tornado episodes in the north central US, mainly through pooling of dew points and lowering of the LCL.

Wet ground from morning precipitation may have contributed to an underestimation of surface moisture by computer model forecasts in this event. The 1800 UTC run of the meso-Eta did an exceptionally good job at depicting most features. It correctly placed the center of the surface low pressure approaching Mitchell at 2100 UTC (the last hour before convective cells formed). It projected a temperature of 29.5°C, only slightly below the actual hourly observation of 30°C (86°F). The meso-Eta also predicted surface winds would back around to the east, which they did. The only feature which significantly differed was dew point. The meso-Eta projected a surface dew point of 20.6°C (69°F). The actual dew point reported at KMHE at 2100 UTC was 25°C (77°F).

The significance of a 3.4°C deviation in the pre-storm dew point can be seen by examining a virtual sounding. The 1800 UTC run of the meso-Eta plotted in RAOB depicts an unstable profile at 2100 UTC, with a surface-based CAPE of 3237 J kg^{-1} (Fig. 42). If the profile is unchanged except for modifying the surface temperature 0.5° to 30°C and the dew point 3.4° to 25°C, matching the surface observation, the CAPE increases to 6299 J kg^{-1} (Fig. 43). A surface-based CAPE >6000 J kg^{-1} is considered "extreme instability" (Thompson, 2003).

Another effect of the increased dew point is the lowering of the LFC. The model extracted LFC height was 1601 m AGL. But when the skew-t is redrawn to account for actual surface observations at 2100 UTC, the height is lowered to just 641 m AGL. An LFC that low suggests rapid low-level ascent, and supercells are more likely to produce tornadoes when they are an environment with an LFC <2000 m AGL (Davies, 2004).

Following the morning convection, numerous low-reflectivity fine lines appeared on WSR-88D radars in Sioux Falls and Aberdeen. Fine lines are concentrated areas of small insects corresponding to low-level convergence, and thus can be considered a possible trigger for thunderstorm development (Serafin et al., 2000; Geerts and Miao, 2005). Wilson and Schreiber (1986) defined boundary layer convergence lines as thin lines of enhanced reflectivity (and/or a line of apparent convergent flow in Doppler velocity), ~1-3 km wide and >10 km long, persisting for a minimum of 15 minutes.

The lines appearing between the Sioux Falls and Aberdeen WSR-88D radars just after noon local time appear to meet this standard (Fig. 44). The Aberdeen radar (KABR) was more sensitive because it was in clear air mode, while Sioux Falls (KFSD) was in precipitation mode due to lingering convection in Minnesota. Most of the echoes were less than 15 dBZ, and were detected at beam heights under 4000 m (13,000 ft). A commonly identified origin of convergence lines is convective outflows, and there were numerous individual thunderstorm cells during the morning.

Differential heating and soil moisture variations due to heavy rainfall are other potential contributing factors to the initiation of severe convection. Soil wetness can also increase CAPE by providing additional boundary layer humidity (Capehart et al., 2004), contributing to convergence boundaries and promoting the convective process. While forecast models earlier in the day underestimated surface moisture, the moisture pooling was seen in the 2100 UTC SPC Mesoscale Analysis (Bothwell et al., 2002). Moisture convergence was occurring along and ahead of the surface front (not shown), and the mesoanalysis (RUC first guess merged with surface observations) showed a localized area of CAPE in excess of 6000 J kg^{-1} in southeast South Dakota (Fig. 45).

During this same mid-afternoon time frame, a portion of the cloud shield over eastern South Dakota had dissipated, allowing solar heating of that increased low level moisture to produce areas of enhanced convective instability. A thick cloud deck remained over western and central South Dakota, attenuating insolation that might have destabilized the atmosphere in those areas. A visible satellite image at 2115 UTC (Fig. 46) shows those features, as well as a supercell forming near Mitchell, South Dakota (location "A" in the image). This supercell produced the first tornado of the evening, the first of what would eventually be 67 tornadoes over the next six hours, the South Dakota tornado outbreak of 24 June 2003.

5. SUMMARY AND CONCLUSIONS

The 67 tornadoes which occurred in South Dakota on 24 June 2003 meet the accepted thresholds of a tornado outbreak, at least quantitatively. A list of previous numerically significant tornado outbreaks in South Dakota was compiled to examine similarities, and it was found the majority of those outbreaks occurred following the rapid advection of low- and mid-level air parcels from their source regions. Specifically, using reanalysis data input to a backward trajectory model, we found 70% of South Dakota's largest single-day outbreaks occurred when moist parcels at 500 m AGL were advected from the Ark-La-Tex region in ≤72 h, and 2500 m AGL dry parcels were advected in ≤24 h from the "four corners" states (UT, CO, AZ, and NM) .

While it is well-known that mT and cT air masses contribute to severe weather, the trajectory analysis allowed us to determine the speed with which the advection of those air masses into South Dakota occurs. In addition, this differential advection implies both buoyancy and, due to the speed and direction of transport, the broad scale shear contributing to those outbreaks.

Other severe weather episodes such as hail, wind, and lesser tornado events in South Dakota during calendar year 2003 were examined to see if there is a similar correlation. We found that other than the single three day severe weather event from 22-24 June (of which the tornado outbreak was a subset), only a few had the rapid low-level advection from the Ark-La-Tex, and none had both the low- and mid-level differential advection as did the tornado outbreaks. We also looked at null cases, defined as the remainder of the warm-season days in 2003, and again found no combination of the low- and mid-level parcel advection other than during the outbreak. While the trend is clear, the tornado outbreak forecast value is still uncertain due to limitations of model-forecast trajectory analysis. Further work is suggested to determine if trajectory analyses can be applied operationally to anticipate tornado outbreaks.

Severe weather parameters such as EHI_{0-1} showed predictive skill in highlighting threat areas. But there were some errors in forecast model guidance, such as an underestimation of surface dew points - probably due to an inability to resolve low-level moisture following morning precipitation. This caused the 1800 UTC meso-Eta to under-forecast SBCAPE at the outbreak initiation location by approximately 3000 J kg^{-1}.

In summary, we conclude the outbreak of 24 June 2003 occurred for these reasons: The atmosphere was sufficiently unstable, and had been for two days. The tornado outbreak was delayed because optimal triggering mechanisms were farther south until 24 June, when a short wave and associated vorticity maximum promoted intensification of the surface low pressure system near where the strongest tornadoes occurred. Buoyancy was aided by swift differential advection of low- and mid-level air parcels, as demonstrated by trajectory analysis.

The scope of the outbreak was climatologically unprecedented. It was also systematically unique because, as will be discussed in the accompanying paper, a significant number of the tornadoes occurred in a region of the storm that would not be characterized as particularly tornado-favorable.

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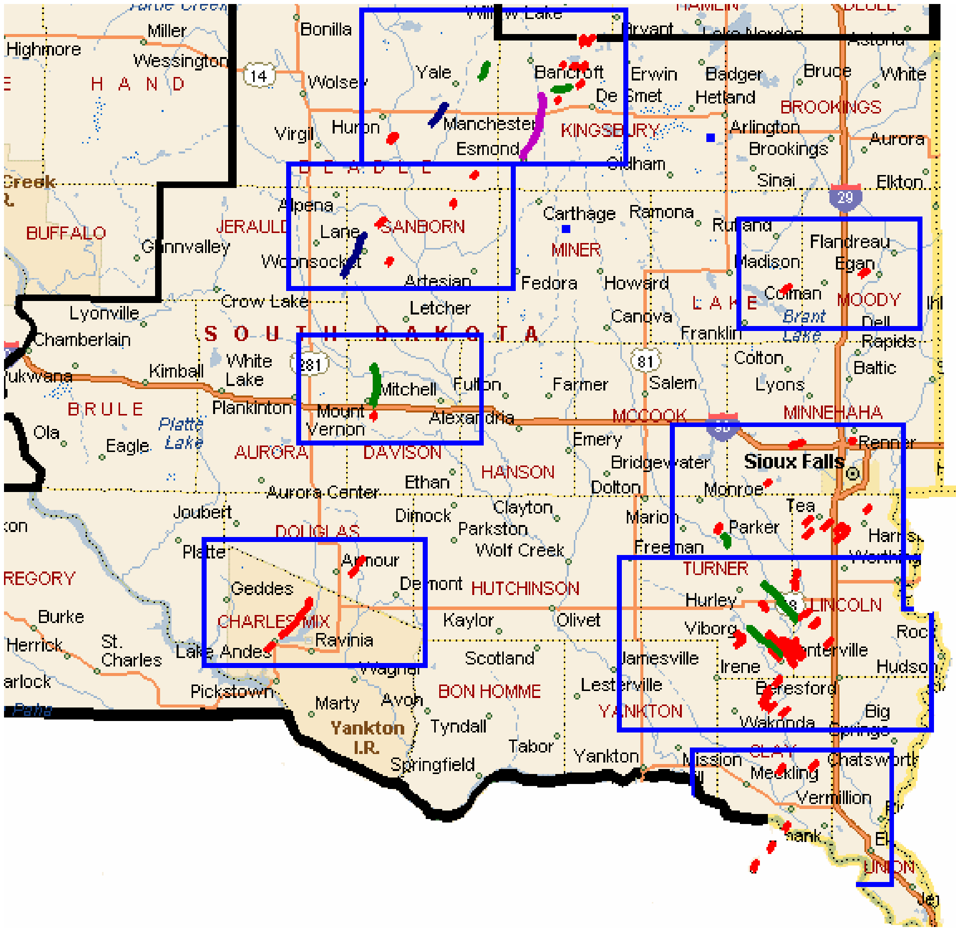


Fig. 1. Tornado paths through east central and southeastern South Dakota as determined in damage survey (from NWS-FSD). Red paths are rated F0-F1, green are F2, blue are F3, and purple is the Manchester F4.

Tornadoes in One Day	State and Date
67	South Dakota – 24 June 2003
67	Texas – 20 September 1967
58	Oklahoma – 3 May 1999

Table 1. Single day tornado records compiled by the NOAA Storm Prediction Center (SPC). Statement available online at http://www.crh.noaa.gov/fsd/wcm/sdtor062403.htm [accessed 2004].

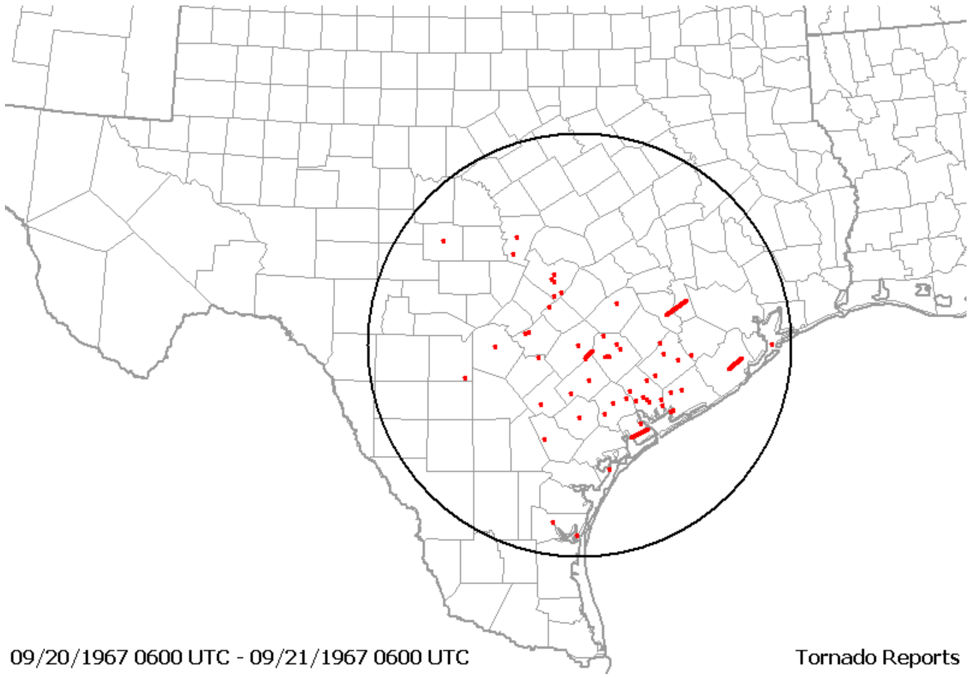


Fig. 2. Locations/paths of the 67 tornadoes in Texas on 20 September 1967. Circle is 700 km wide, centered on Gonzales. Map created with SPC SeverePlot v2.5 (Hart, 2003) software.

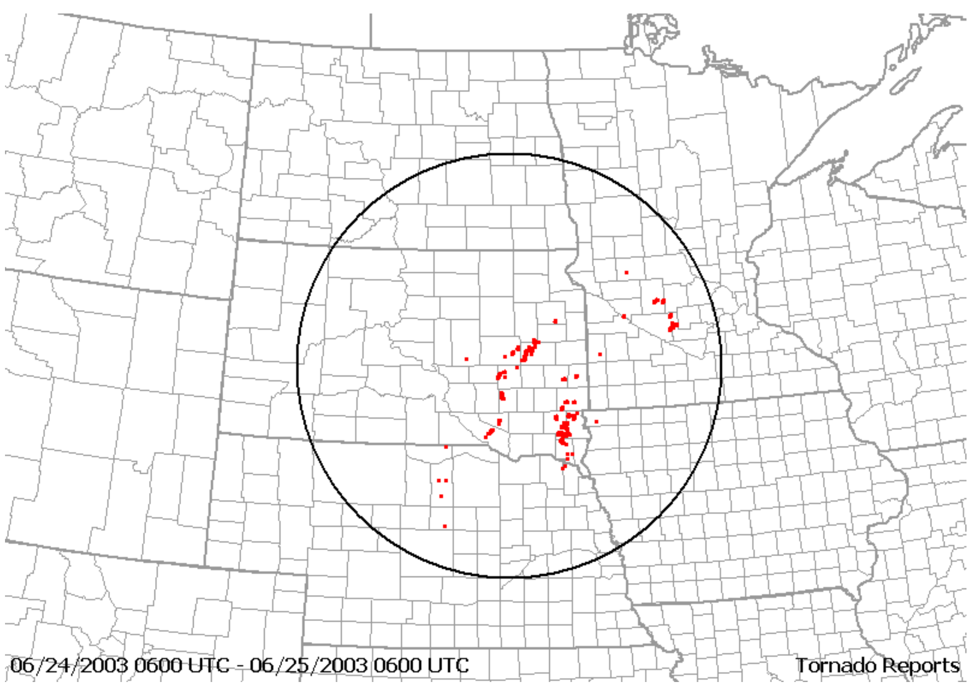


Fig. 3. Locations/paths of the 67 tornadoes in South Dakota on 24 June 2003 (additional tornadoes visible in adjoining states). Circle is 700 km wide, centered on Huron. Scale same as Fig. 2.

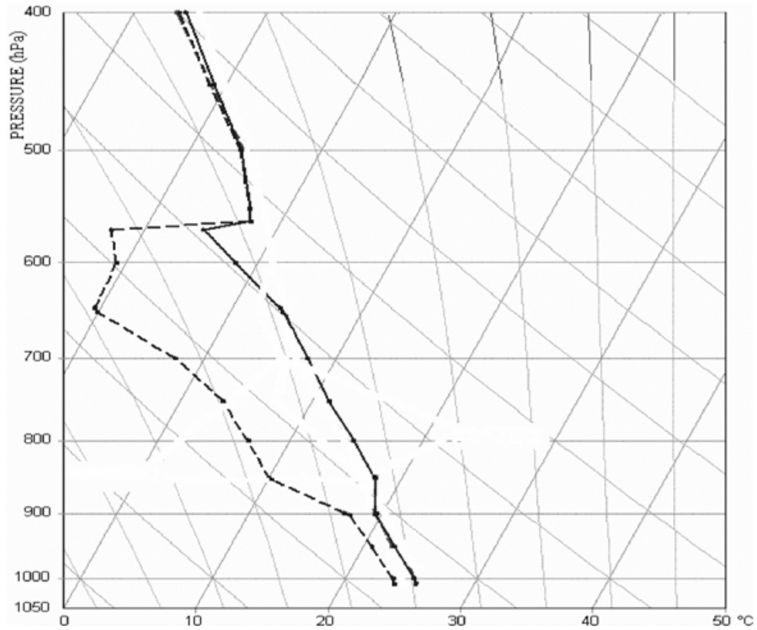


Fig. 4. Sounding from Victoria, TX at 1200 UTC 22 September 1967. Adapted from Curtis (2004).

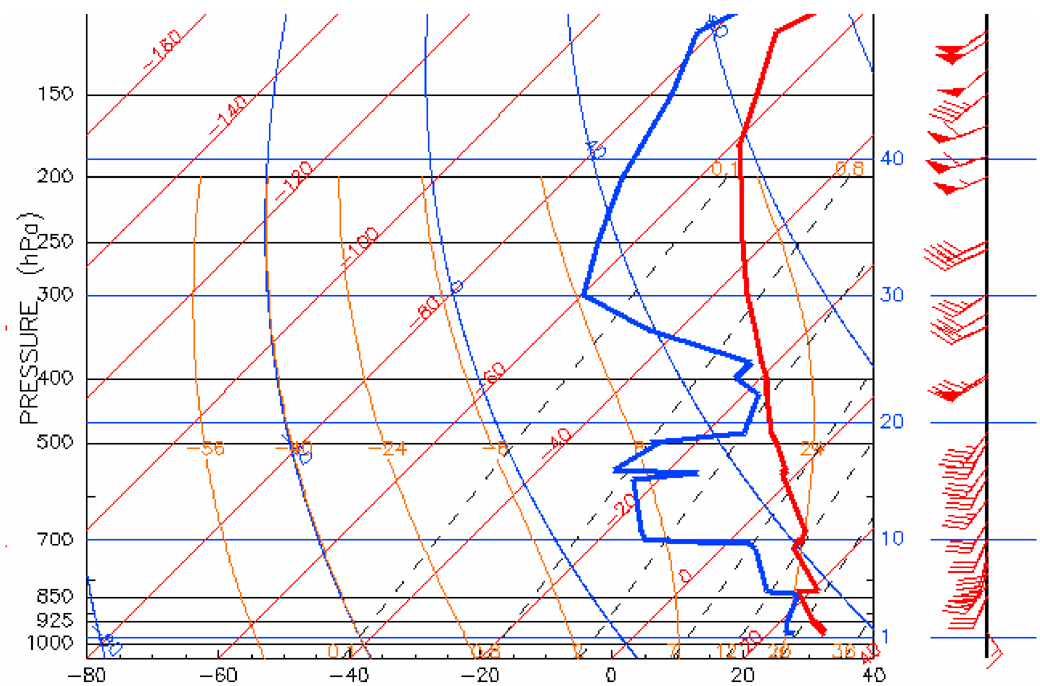


Fig. 5. Sounding from OAX (Omaha) at 0000 UTC on 25 June 2003. From NOAA Forecast Systems Laboratory (available online at http://raob.fsl.noaa.gov/ [accessed 2005]).

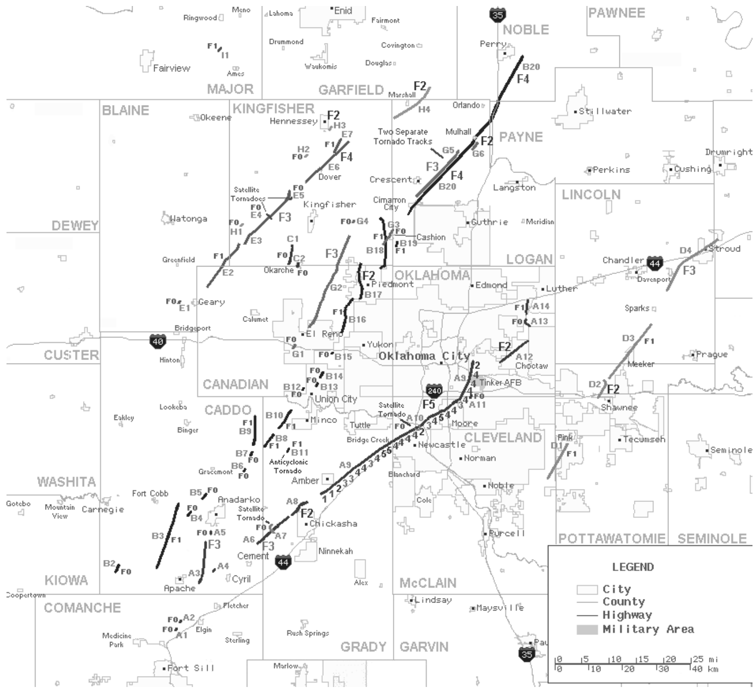


Fig 6. Tornado paths through NWS Norman, OK County Warning Area on 3 May 1999 (from Speheger, 2001).

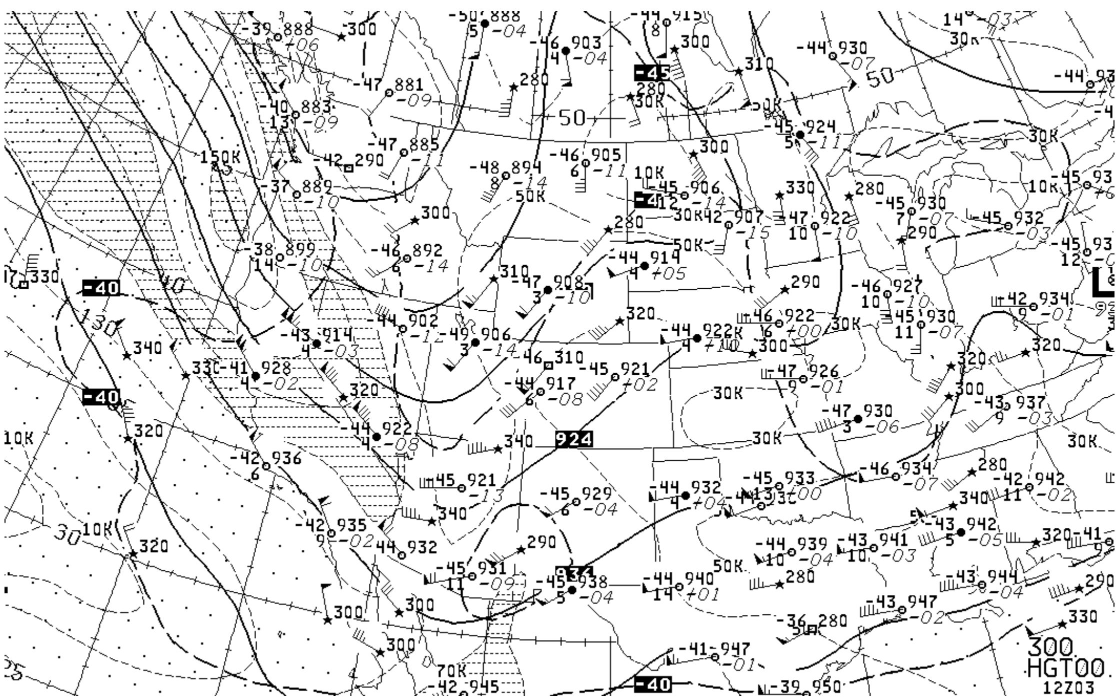


Fig. 7. 300 hPa isotach (kt) and geopotential heights analysis, 1200 UTC, 3 May 1999 (from NCDC, available online at http://nomads.ncdc.noaa.gov/ncep-charts/archives/19990503/fm2dotfx.12.2368.1728.1900.gif).

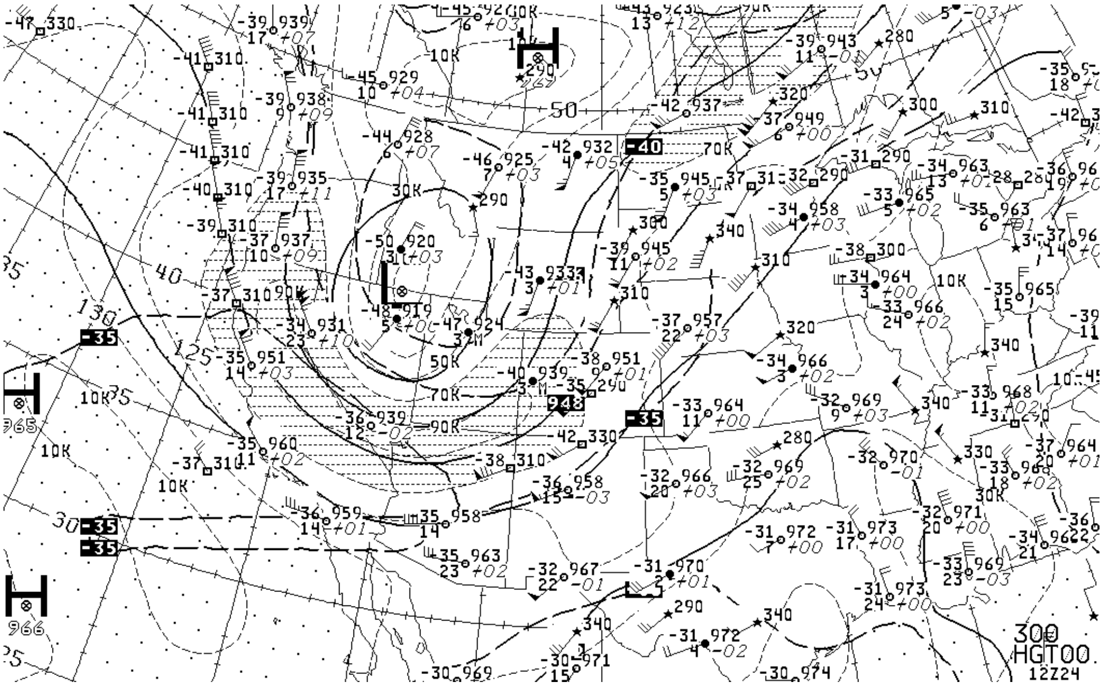


Fig. 8. 300 hPa isotach (kt) and geopotential heights analysis, 1200 UTC, 24 June 2003 (from NCDC, available online at http://nomads.ncdc.noaa.gov/ncep-charts/archives/20030624/fm2dotfx.12.2368.1728.1900.gif).

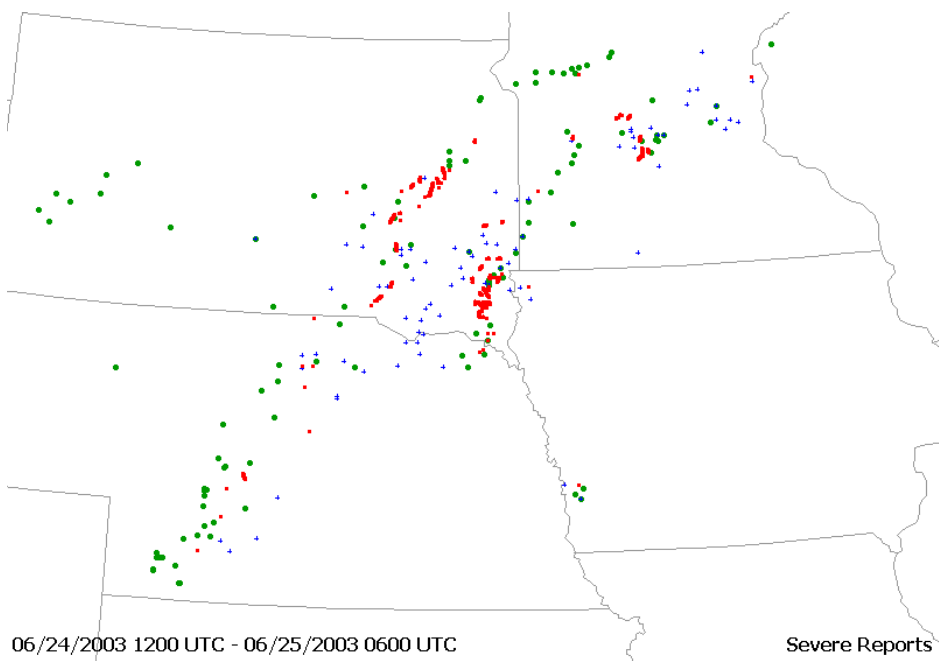


Fig. 9. Plot of SPC severe storm reports from four states in the upper Midwest for the 18 hour period from 0600 to midnight local standard time 24 June 2003. Tornadoes are in red, hail reports in blue, and damaging wind reports in green. Created with SeverePlot v2.5 software previously referenced.

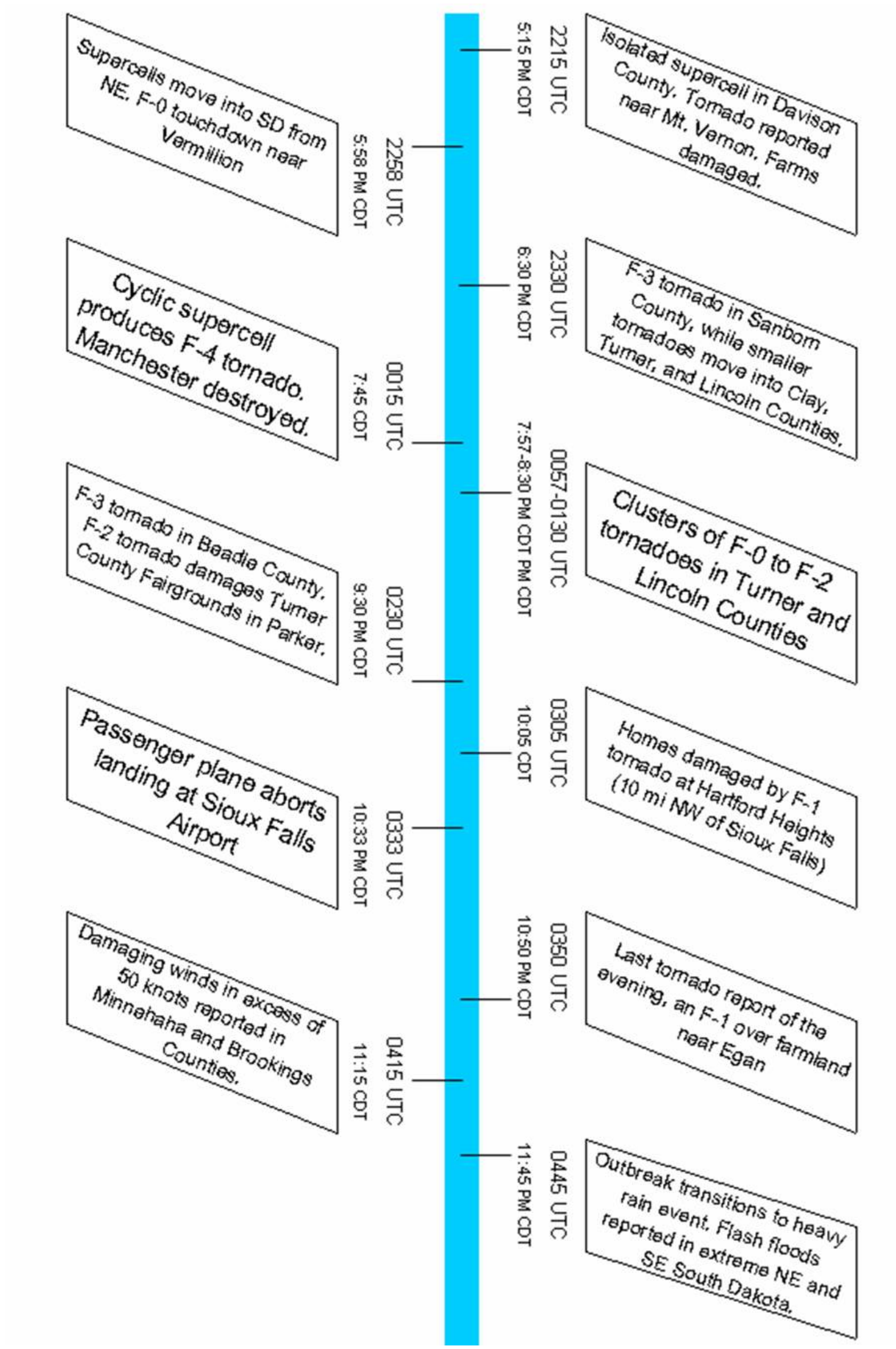


Fig. 10. Timeline of selected events during the severe weather outbreak of 24 June 2003. From official storm data reports, compiled at the National Climatic Data Center.

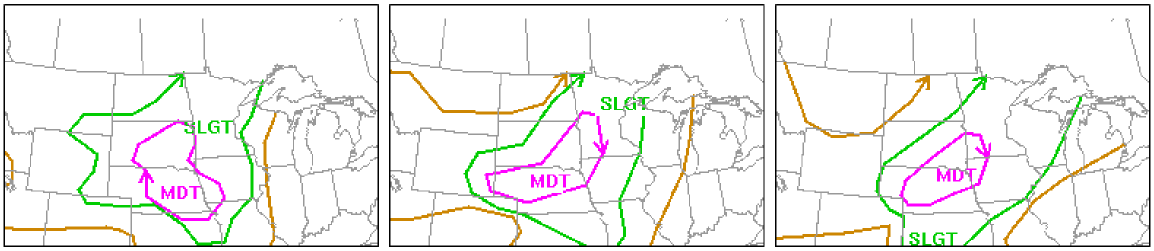


Fig. 11. Daily convective outlooks (1630 UTC) from the SPC. From left to right, 22 June, 23 June, and 24 June, 2003. Areas of moderate risk (MDT) are indicated.

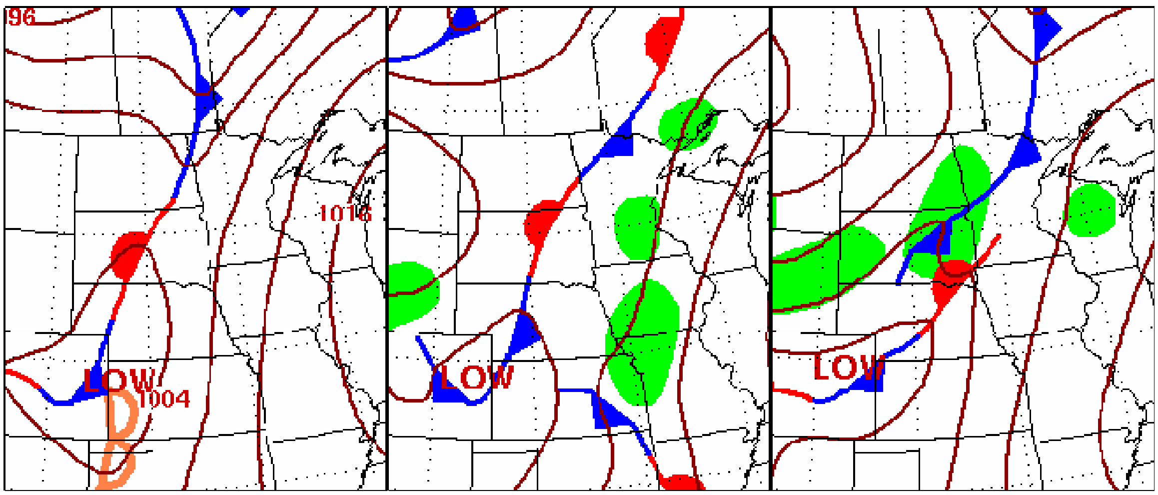


Fig. 12. 1200 UTC Surface maps from 22 June, 23 June, and 24 June, 2003. Green indicates areas of observed precipitation. Note the consistent position of frontal boundaries over the Northern Plains (NOAA-HPC, 2003).

ABR Sounding	700 mb temp (°C)	CIN (J/kg)	LFC (mb)	CAPE (J/kg)	Lifted Index	Precip. Water (mm)	Bulk Richardson Number
00Z 22 Jun 2003	9.8	-1.96	866.35	4558.69	-13.11	46.58	86.83
12Z 22 Jun 2003	5.8	-349.37	556.20	43.48	-1.31	31.07	12.00
18Z 22 Jun 2003	9.4	-51.97	733.48	963.12	-4.43	34.79	25.95
00Z 23 Jun 2003	7.0	-10.99	836.83	1807.32	-5.16	38.27	33.44
12Z 23 Jun 2003	7.0	-34.80	782.32	2975.16	-9.17	35.18	49.31
18Z 23 Jun 2003	6.8	-243.38	623.14	468.90	-2.77	28.31	4.55
00Z 24 Jun 2003	7.0	-28.22	804.97	2127.46	-4.72	35.58	16.32
18Z 24 Jun 2003	7.0	-3.56	863.15	165.88	0.33	31.03	1.96
00Z 25 Jun 2003	9.0	-261.02	536.91	674.42	-1.11	38.78	2.49

Table 2. Selected severe weather parameters from ABR soundings 22 June 2003-25 June 2003. Data from University of Wyoming archive, available online at http://weather.uwyo.edu/upperair/naconf.html.

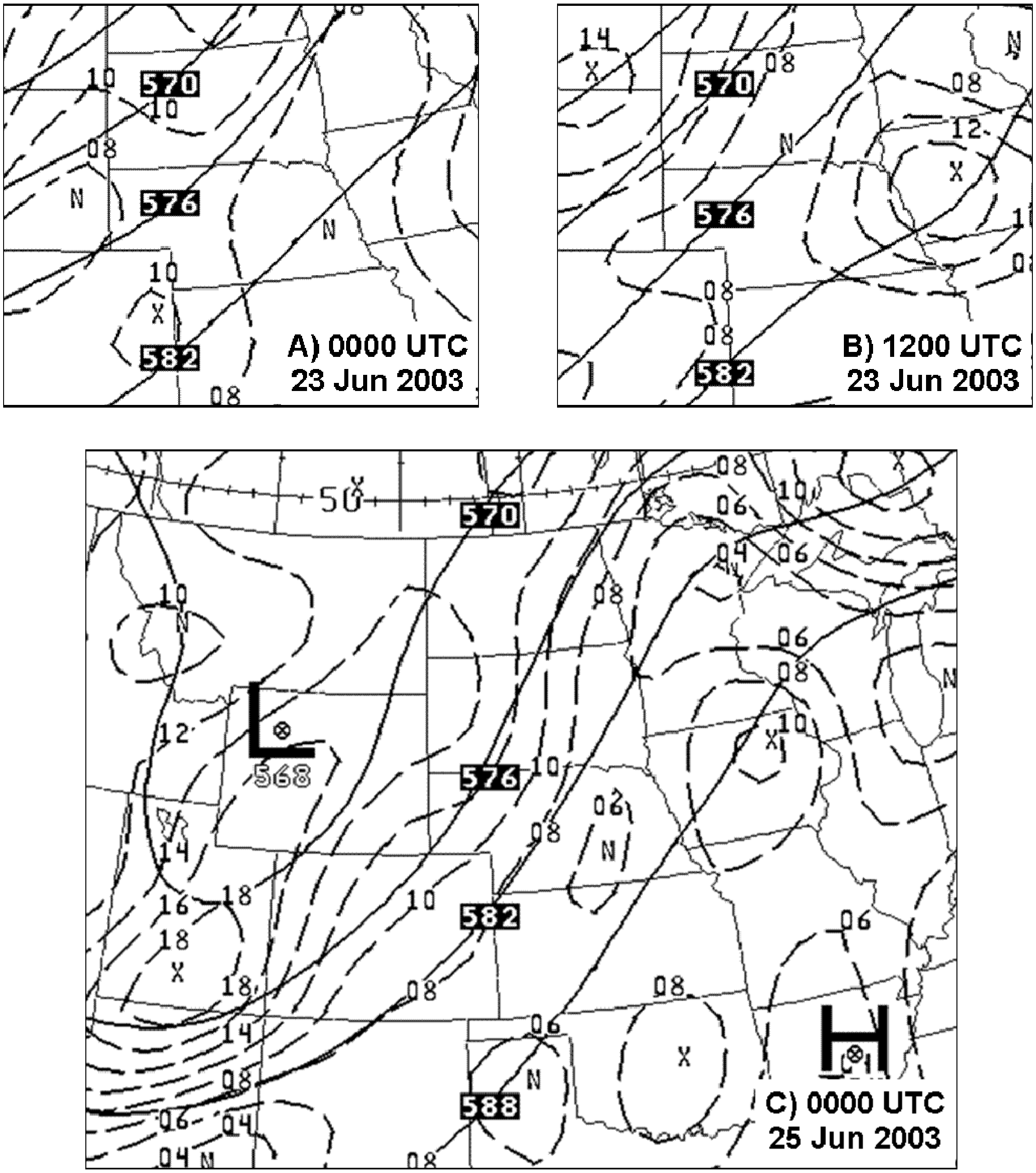


Fig. 13a-c. NCEP 500 hPa heights and vorticity from **a**) 1200 UTC 23 June 2003, **b**) 1200 UTC 23 June 2003, and **c**) 0000 UTC 25 June 2003. Available online at http://nomads.ncdc.noaa.gov/ncep-charts/.

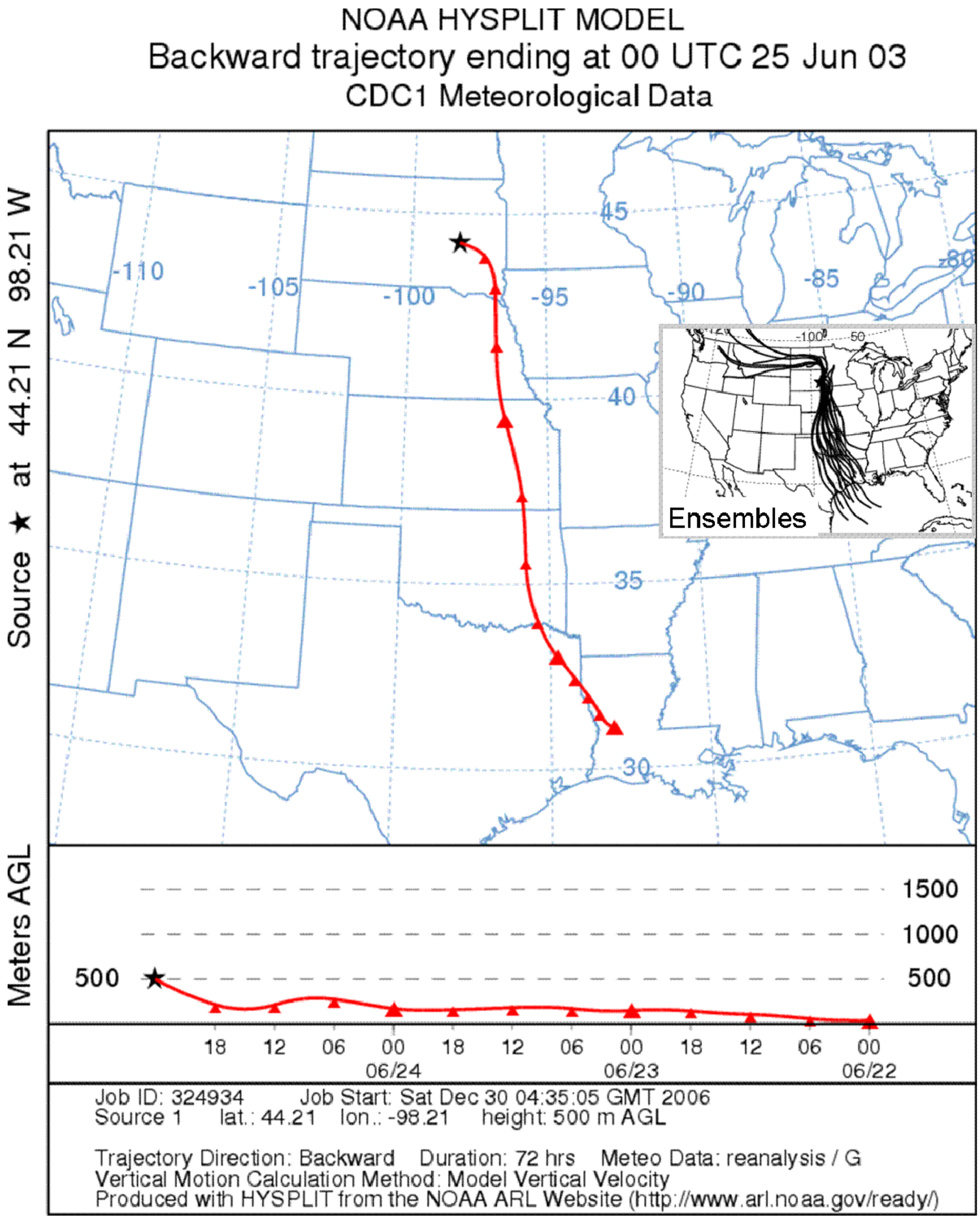


Fig. 14. 72-hour trajectory of an air parcel, calculated from NCEP/NCAR reanalysis data with a final location at Huron, SD at 2200 UTC on 24 June 2003. Larger triangles represent 0000 UTC positions, and smaller triangles represent 1200 UTC positions.

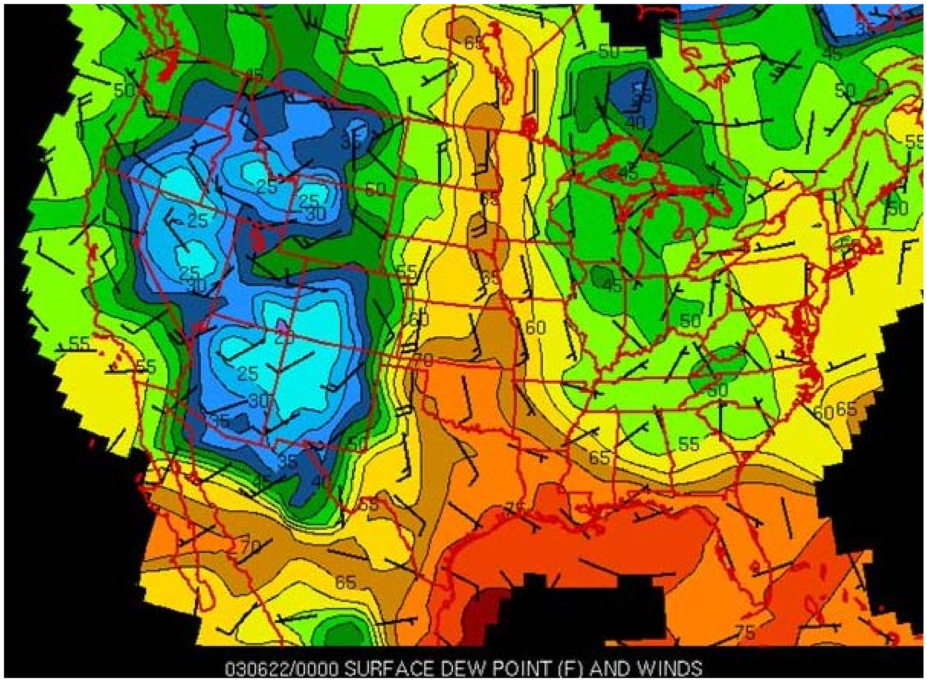


Fig. 15. Surface dew point contours at 0000 UTC on 22 June 2003, beginning hour of the previously referenced backward trajectory analysis. Orange colors indicate dew points >70°F. From Iowa State University, online at http://www.pals.iastate.edu/archivewx/data/.

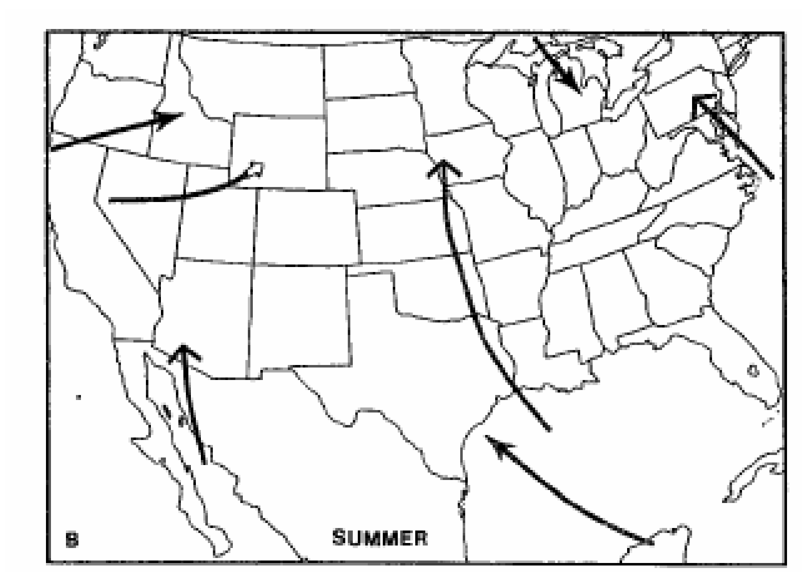


Fig. 16. Composite representation of major source regions of surface moist air masses, with arrow tails indicating the source region and arrowheads approximating the mean extent of the leading edge of the air mass. From Hagemeyer, 1991.

Fig. 17. Mosaic of tornado tracks, 1950-2003. Created from SPC storm reports with SeverePlot v2.5 (Hart, 2003) software.

Date	Number of tornado reports	Approximate location centroid of tornado reports	Local time of first report
24 June 2003	67	Huron	5:00 PM
7 June 1993	28	Howard	2:30 PM
11 May 1985	20	Mitchell	3:22 PM
4 June 1980	20	Kadoka	1:45 PM
16 June 1992	17	Salem	1:30 PM
24 May 1965	16	Parker	1:57 PM
6 July 1987	14	Kennebec	4:00 PM
28 May 2004	13	Beresford	6:04 PM
29 May 1980	13	Huron	2:42 PM
19 June 1979	13	Alexandria	2:55 PM
8 May 1965	13	Winner	12:15 PM

Table 3. Ranking of multiple tornado report days in South Dakota between 1950 and 2005. Compiled from Grazulis (1993) and NCDC (2006).

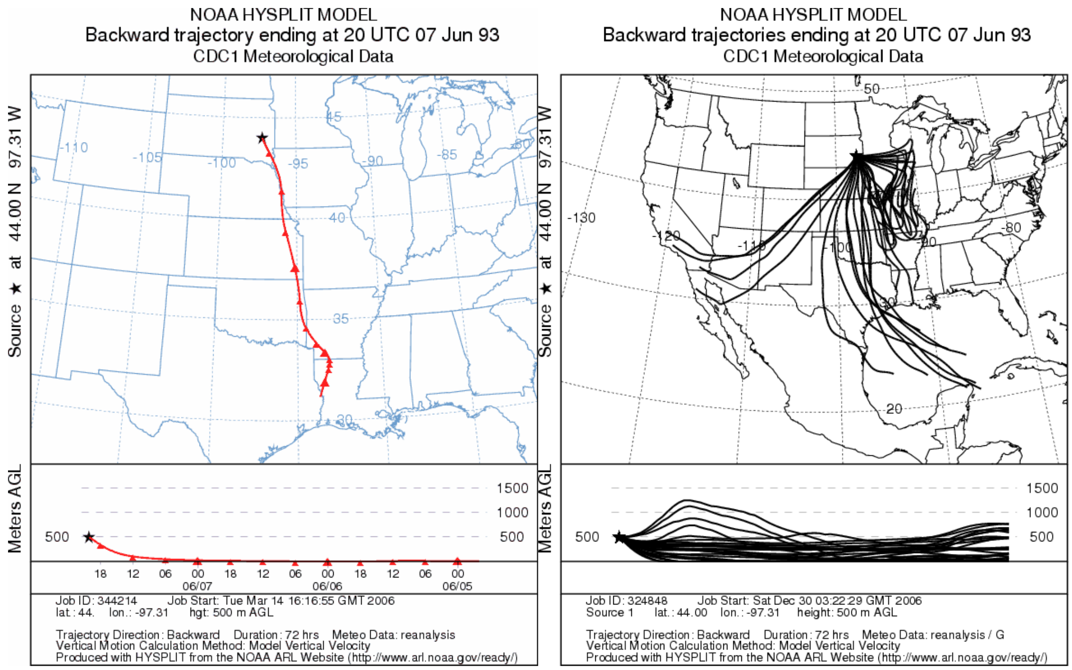


Fig. 18a. Backward trajectory and trajectory ensembles from 7 June 1993 tornadoes.

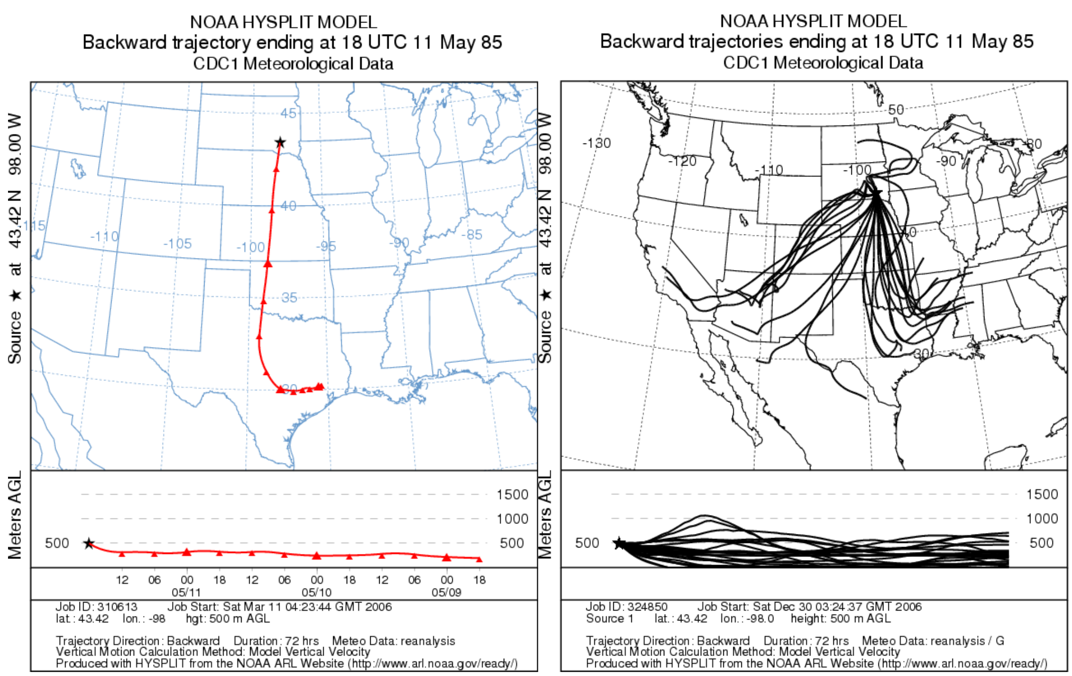


Fig. 18b. Backward trajectory and trajectory ensembles from 11 May 1985 tornadoes.

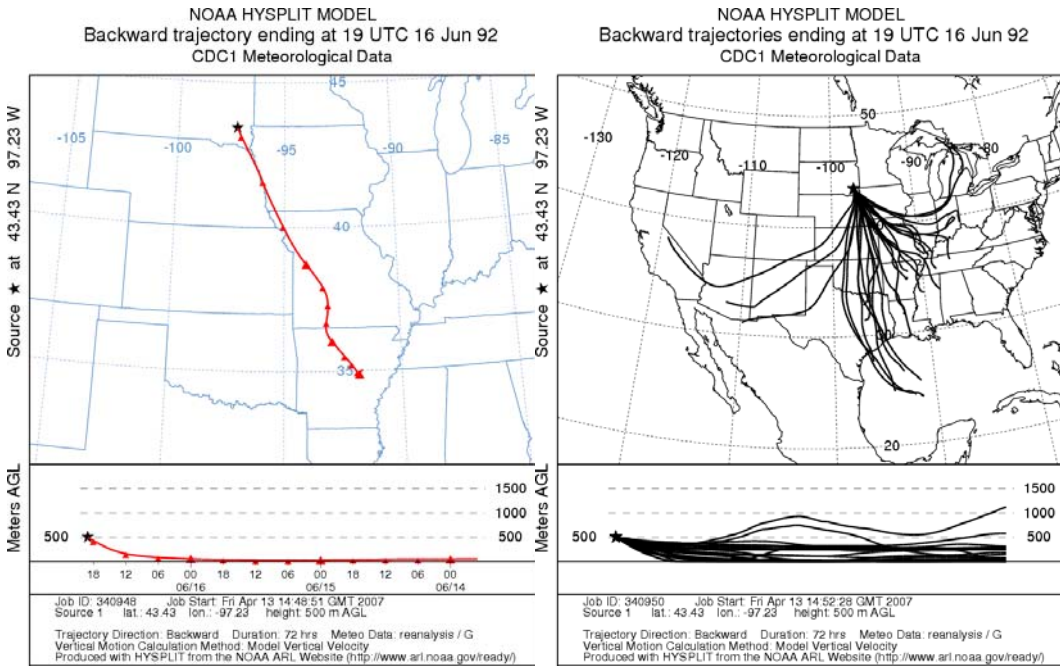


Fig. 18c. Backward trajectory and trajectory ensembles from 16 June 1992 tornadoes.

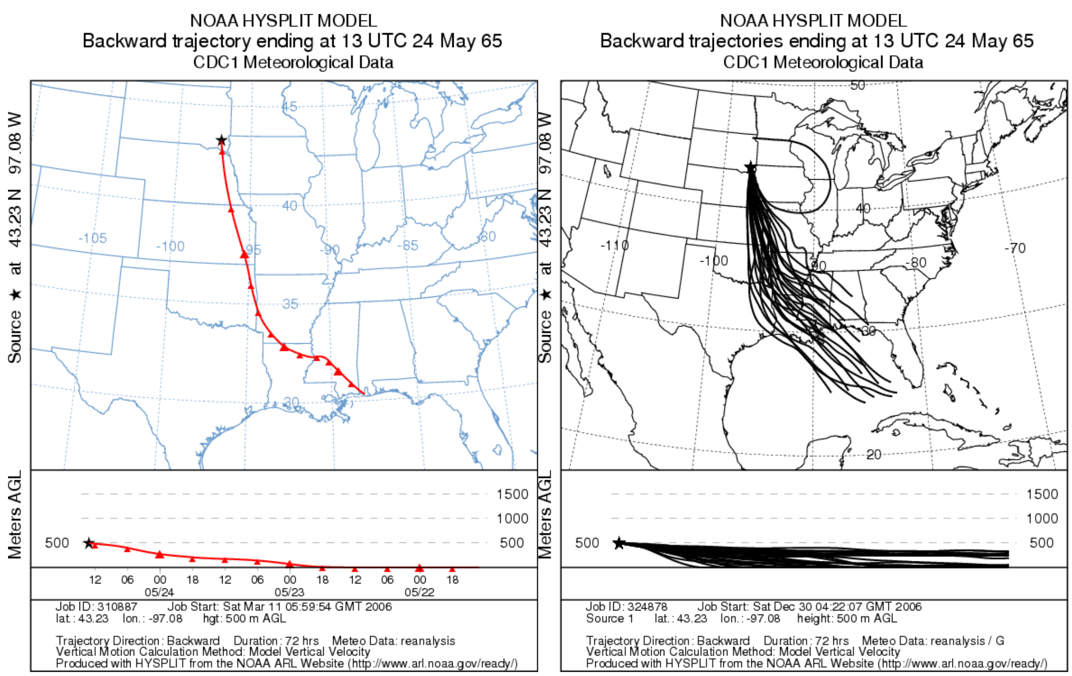


Fig. 18d. Backward trajectory and trajectory ensembles from 24 May 1965 tornadoes.

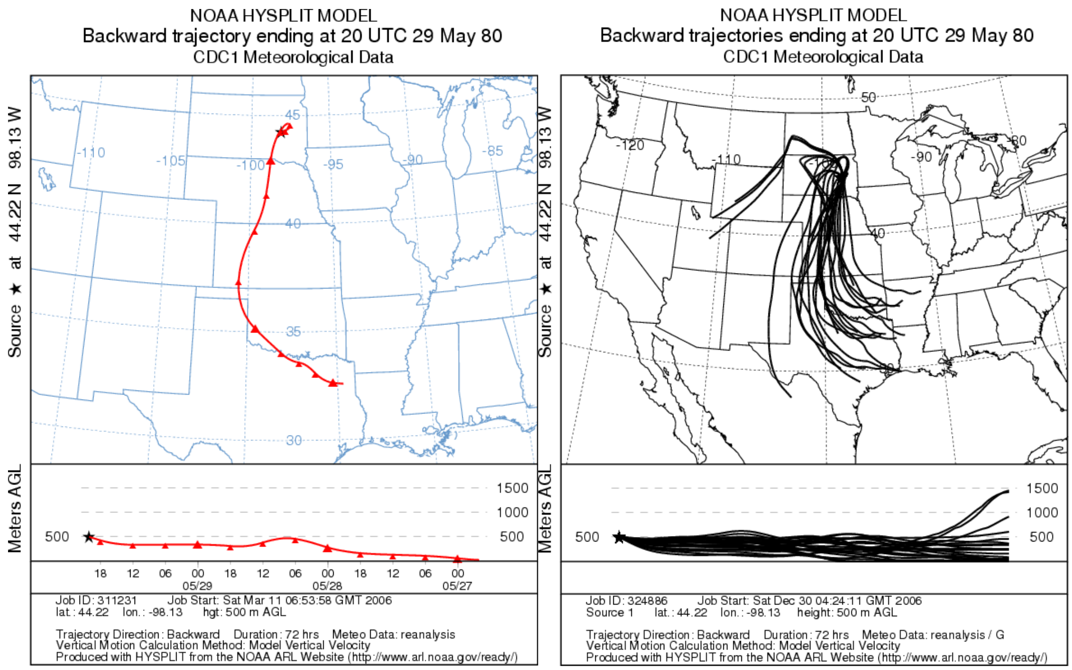


Fig. 18e. Backward trajectory and trajectory ensembles from 29 May 1980 tornadoes.

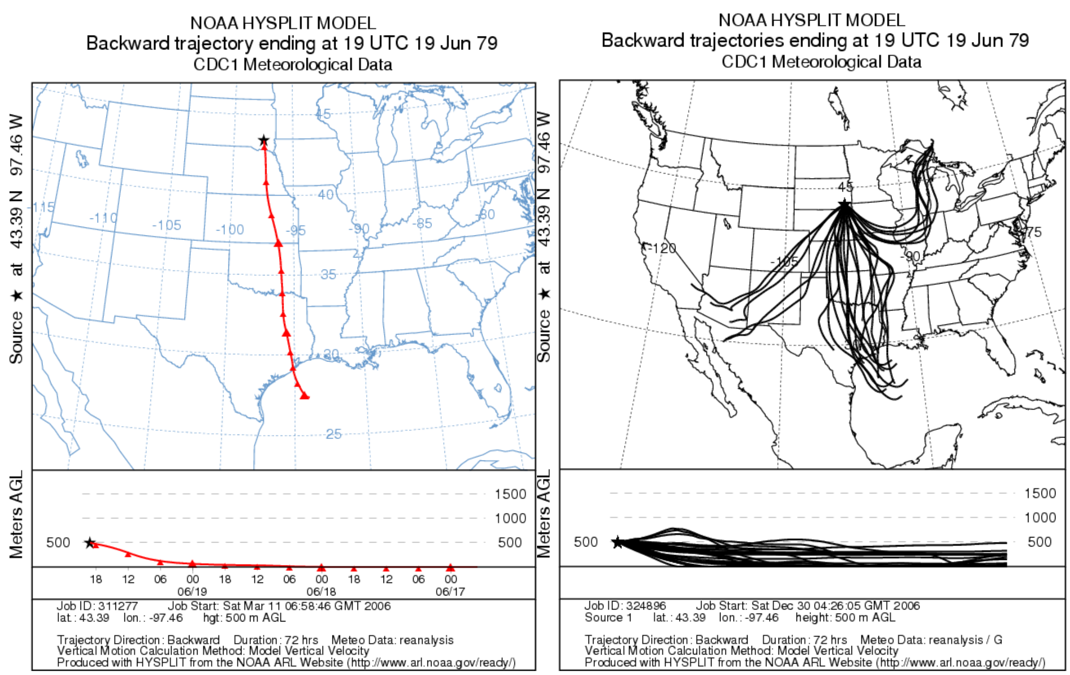


Fig. 18f. Backward trajectory and trajectory ensembles from 19 June 1979 tornadoes.

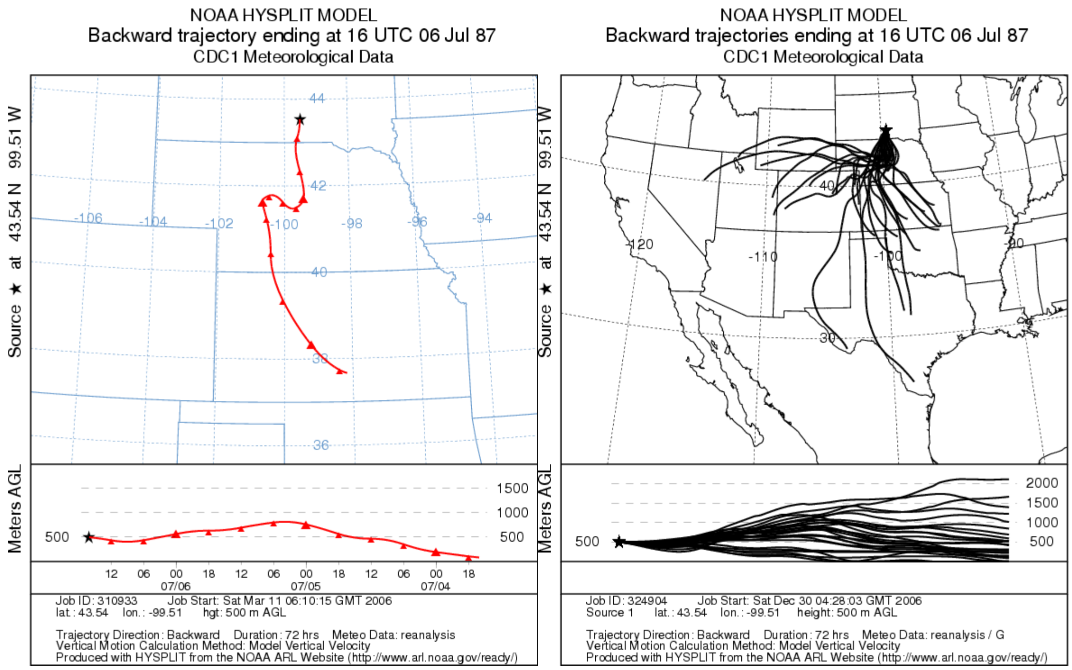


Fig. 18g, Backward trajectory and trajectory ensembles from 6 July 1987 tornadoes.

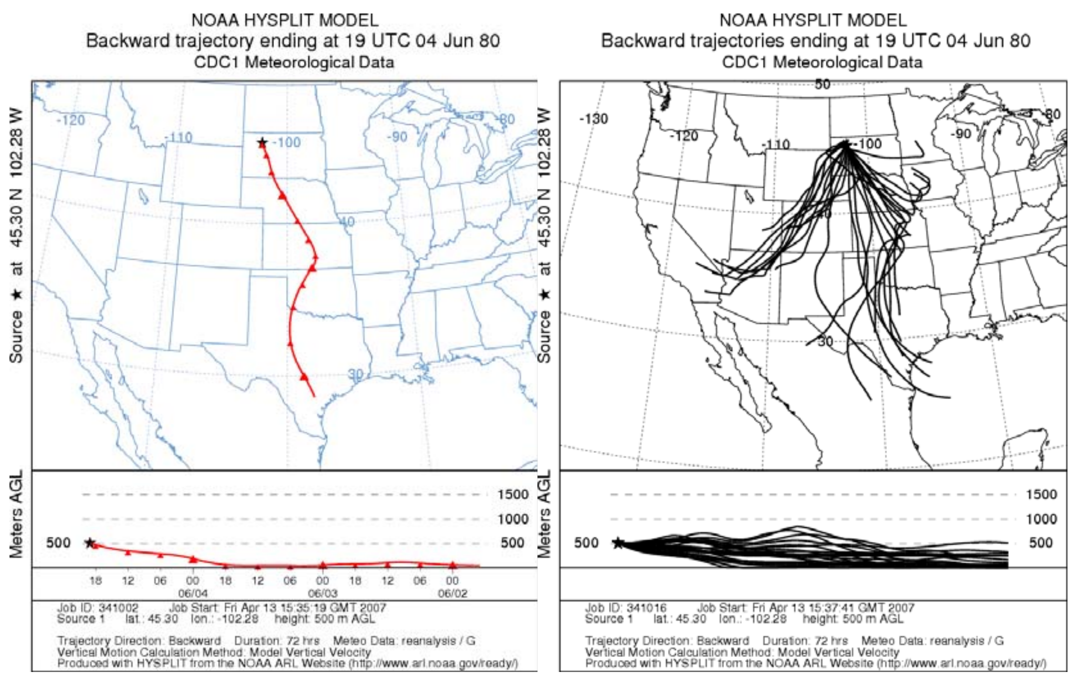


Fig. 18h. Backward trajectory and trajectory ensembles from 4 June 1980 tornadoes.

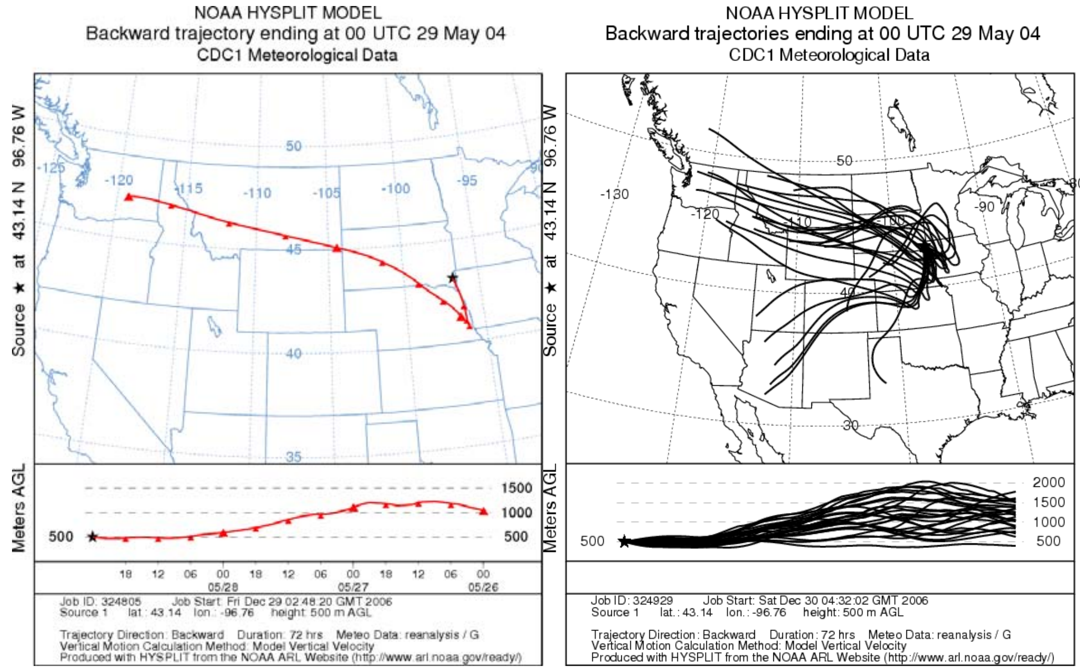


Fig. 18i. Backward trajectory and trajectory ensembles from 28 May 2004 tornadoes.

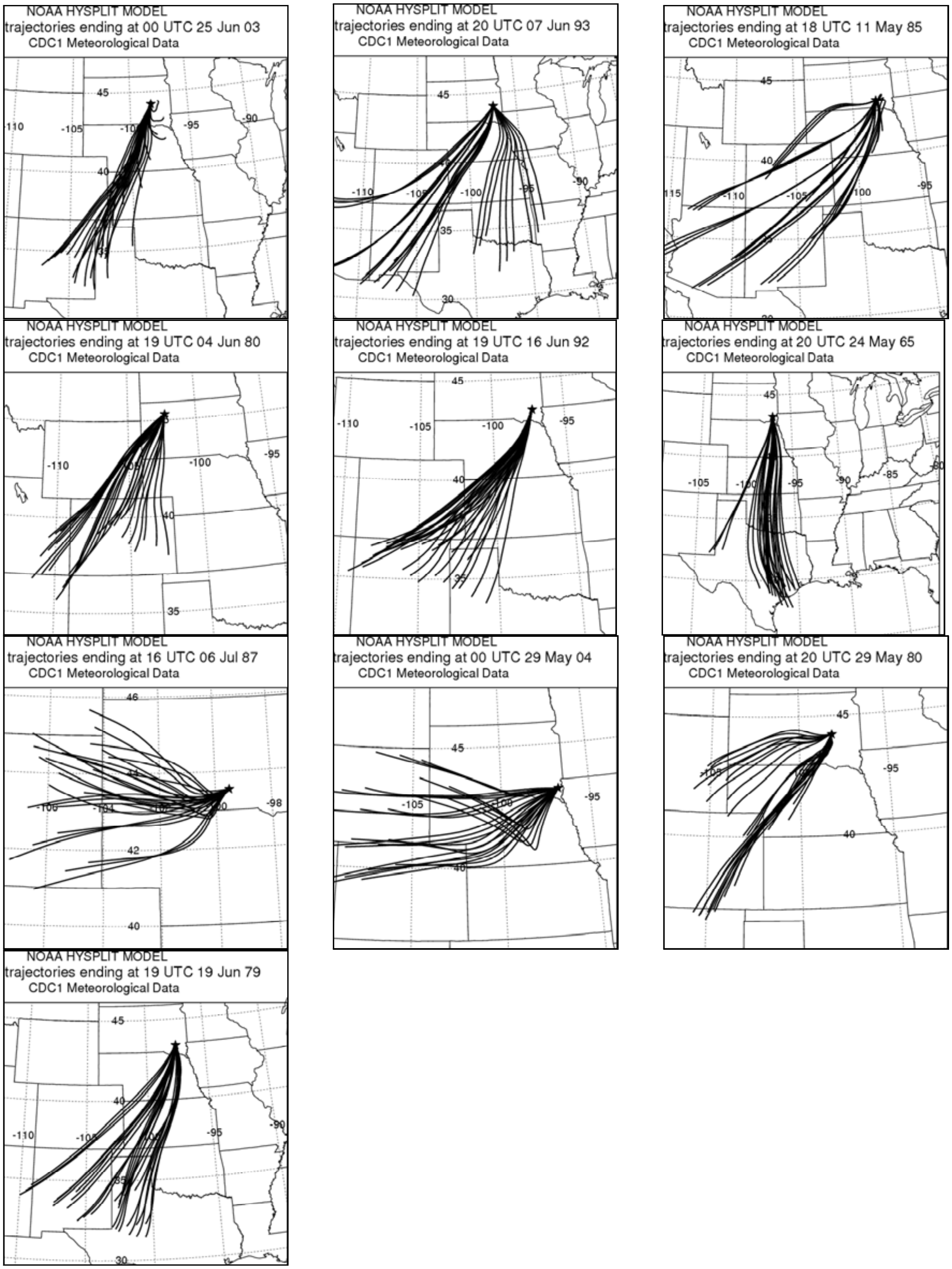


Fig. 19. Ensemble backward trajectories of 2500 m AGL endpoints for ten largest tornado outbreak days in South Dakota, in order of magnitude starting with 24 June 2003 upper left.

2003 SD Storm reports				First storm report			
Date	Tor	Hail	Wind	Time	Location	Lat	Lon
3 May	3	16	0	2035	Sturgis	44.36	103.43
4 May	4	5	0	2130	Hidden Timber	43.26	100.43
29 May	0	3	0	2130	Hub City	43.06	96.72
31 May	0	1	1	0130	Pine Ridge	43.03	102.56
5 June	0	15	0	1820	Madison	44.08	97.11
9 June	3	38	5	0015	Winner	43.33	99.86
10 June	0	2	0	2340	Edgemont	43.22	103.73
11 June	5	15	1	0042	Gettysburg	44.86	100.86
12 June	0	3	0	1935	Rapid City	43.90	103.46
13 June	0	7	0	1930	Custer	43.73	103.64
16 June	0	12	1	1918	Burke	43.18	99.30
17 June	0	3	0	1745	Pine Ridge	43.18	102.56
20 June	0	1	9	2341	Edgemont	43.29	103.83
21 June	0	28	8	2040	Newell	45.02	102.99
22 June	0	5	2	2000	Turton	45.05	98.10
23 June	1	12	6	0050	Waubay	45.28	97.24
24 June	38	35	15	2200	Woonsocket	44.04	98.26
27 June	0	10	8	2020	Buffalo	45.71	103.55
30 June	0	13	0	2355	Cedar Butte	43.64	101.09
1 July	0	8	0	0140	Keystone	43.90	103.41
3 July	2	23	29	0202	Martin	43.16	101.58
4 July	0	24	13	2022	Spearfish	44.49	104.03
5 July	0	25	4	1328	Martin	43.16	101.74
7 July	0	6	2	0434	Dimock	43.48	97.98
8 July	1	20	19	0019	Belle Fourche	44.76	103.86
13 July	0	7	8	0115	Onida	44.51	100.33
14 July	0	6	0	1210	Yale	44.57	97.90
17 July	1	23	1	2345	Red Shirt	43.66	102.90
19 July	0	17	2	2235	Belle Fourche	45.03	103.86
29 July	0	8	8	1721	Rapid City	43.99	103.21
3 Aug	0	2	1	0205	Buffalo Gap	43.49	103.04
4 Aug	0	5	3	2307	Mission	43.24	100.58
20 Aug	0	3	0	2145	Hillsview	45.66	99.25
25 Aug	0	3	0	2342	Aberdeen	45.71	98.62
27 Aug	0	3	2	2220	Prairie City	45.53	102.81

Table 4. Storm reports for 2003 from severe weather episodes affecting South Dakota in 2003. From SPC, available online at http://www.spc.noaa.gov/exper/archive/events/index.html.

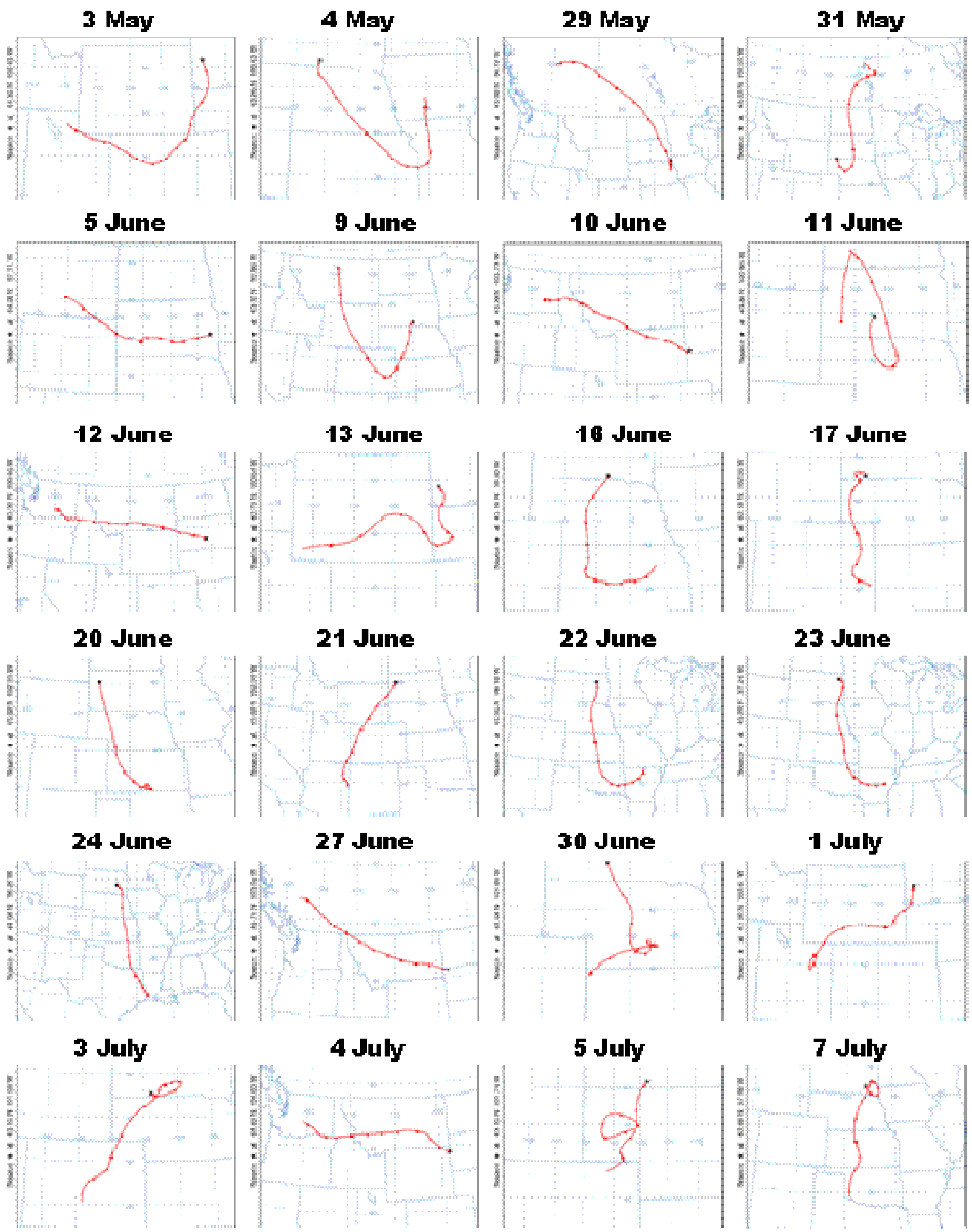


Fig. 20. Backward trajectories ending 500 m AGL from severe weather episodes affecting South Dakota from 3 May-7 July, 2003.

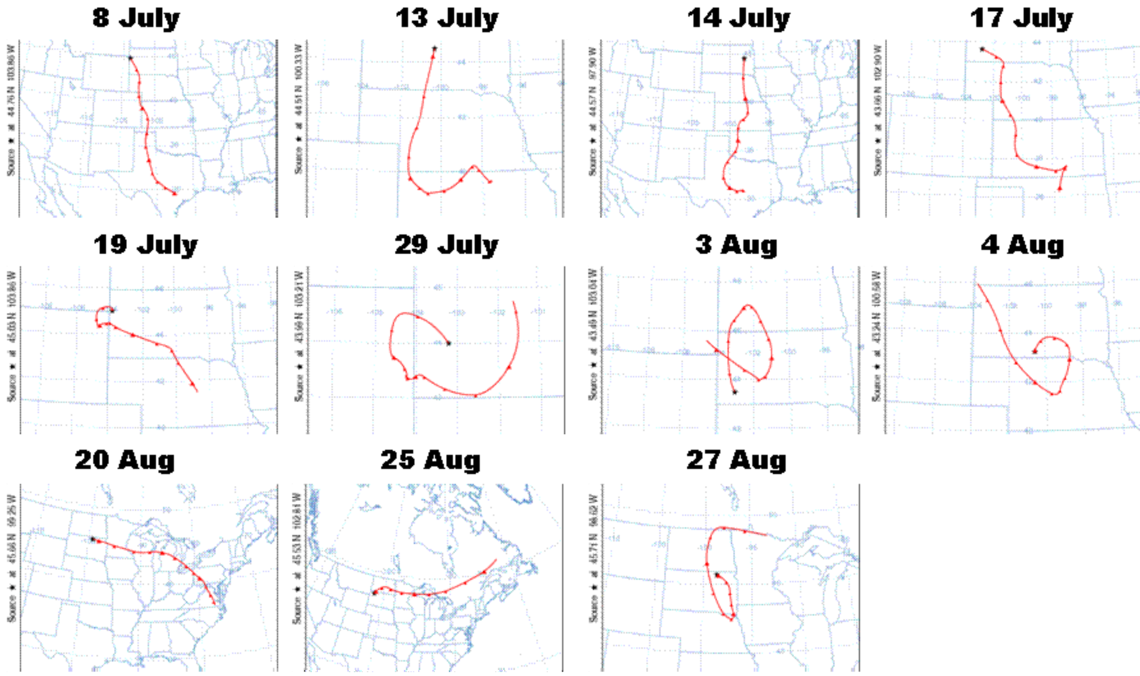


Fig. 21. Backward trajectories from severe weather episodes affecting South Dakota from 8 July-27 August, 2003.

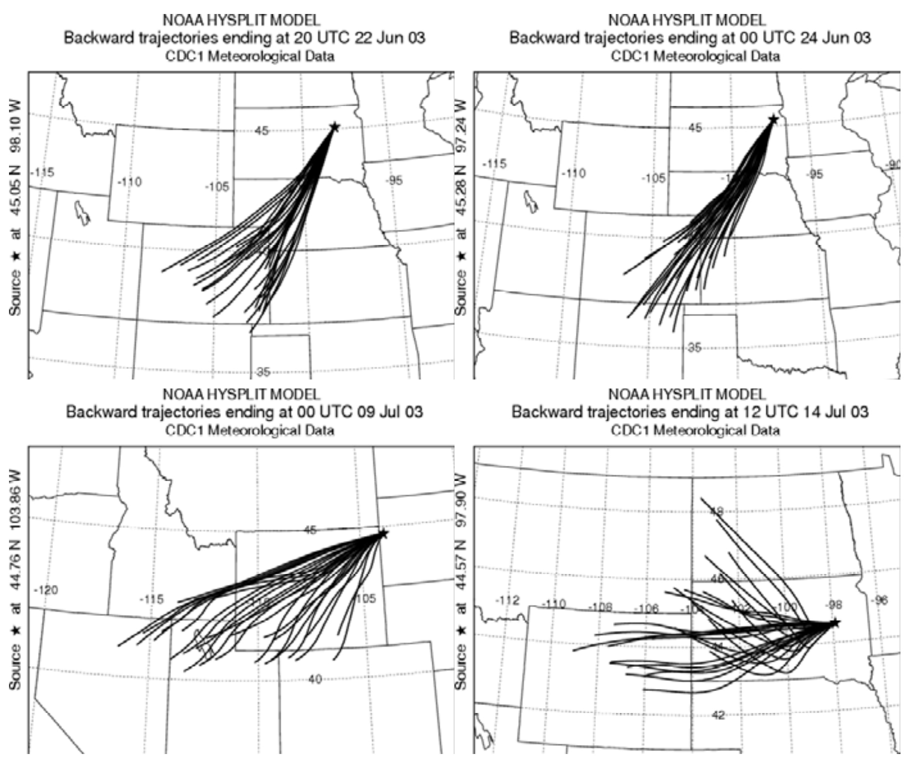
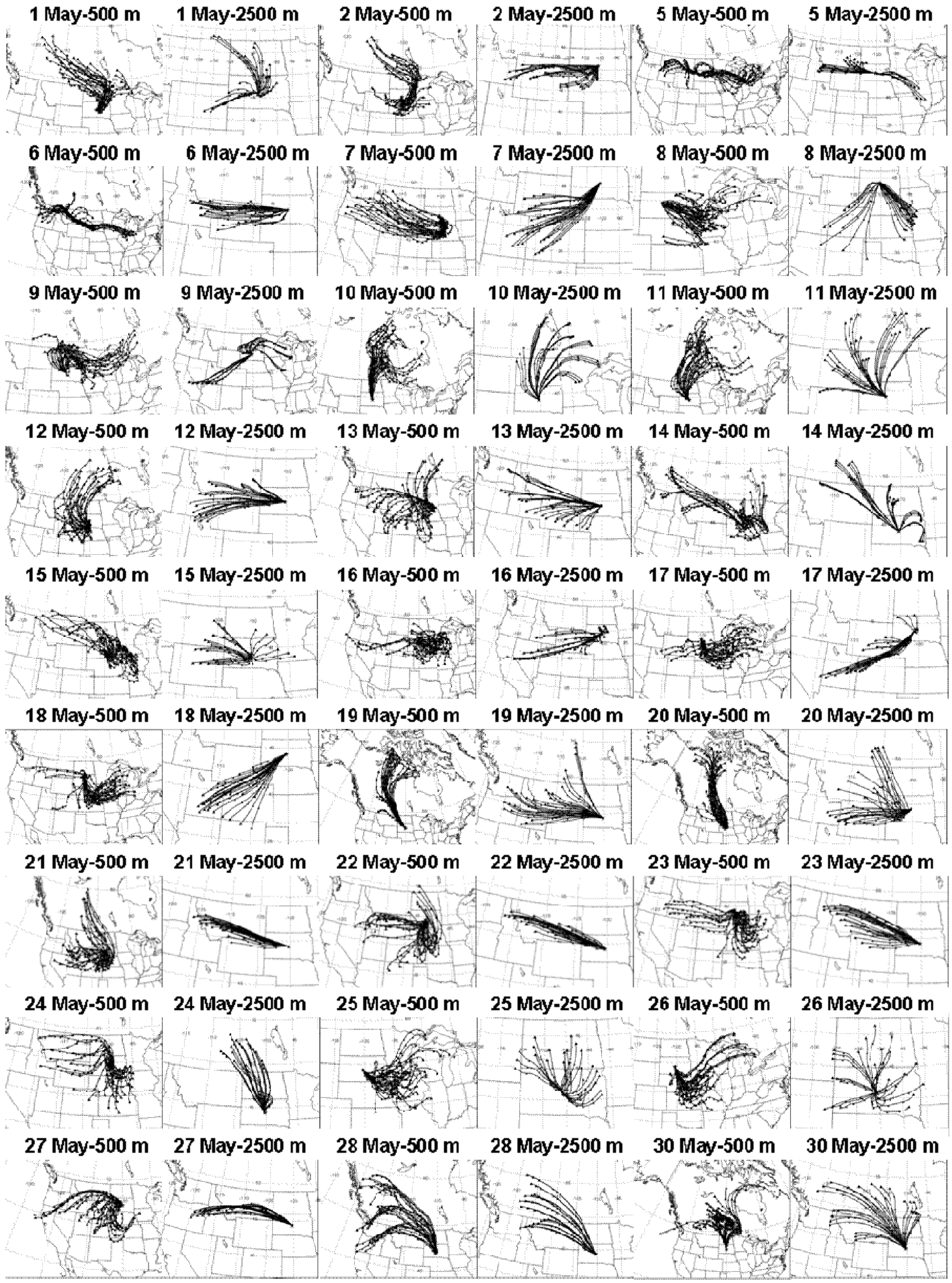


Fig. 22. Backward trajectories from selected episodes in 2003, taken from same endpoint as Fig. 20-21, except ensembles from height of 2400 m AGL.


1 May-500 m
1 May-2500 m
2 May-500 m
2 May-2500 m
5 May-500 m
5 May-2500 m
6 May-500 m
6 May-2500 m
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7 May-2500 m
8 May-500 m
8 May-2500 m
9 May-500 m
9 May-2500 m
10 May-500 m
10 May-2500 m
11 May-500 m
11 May-2500 m
12 May-500 m
12 May-2500 m
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13 May-2500 m
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14 May-2500 m
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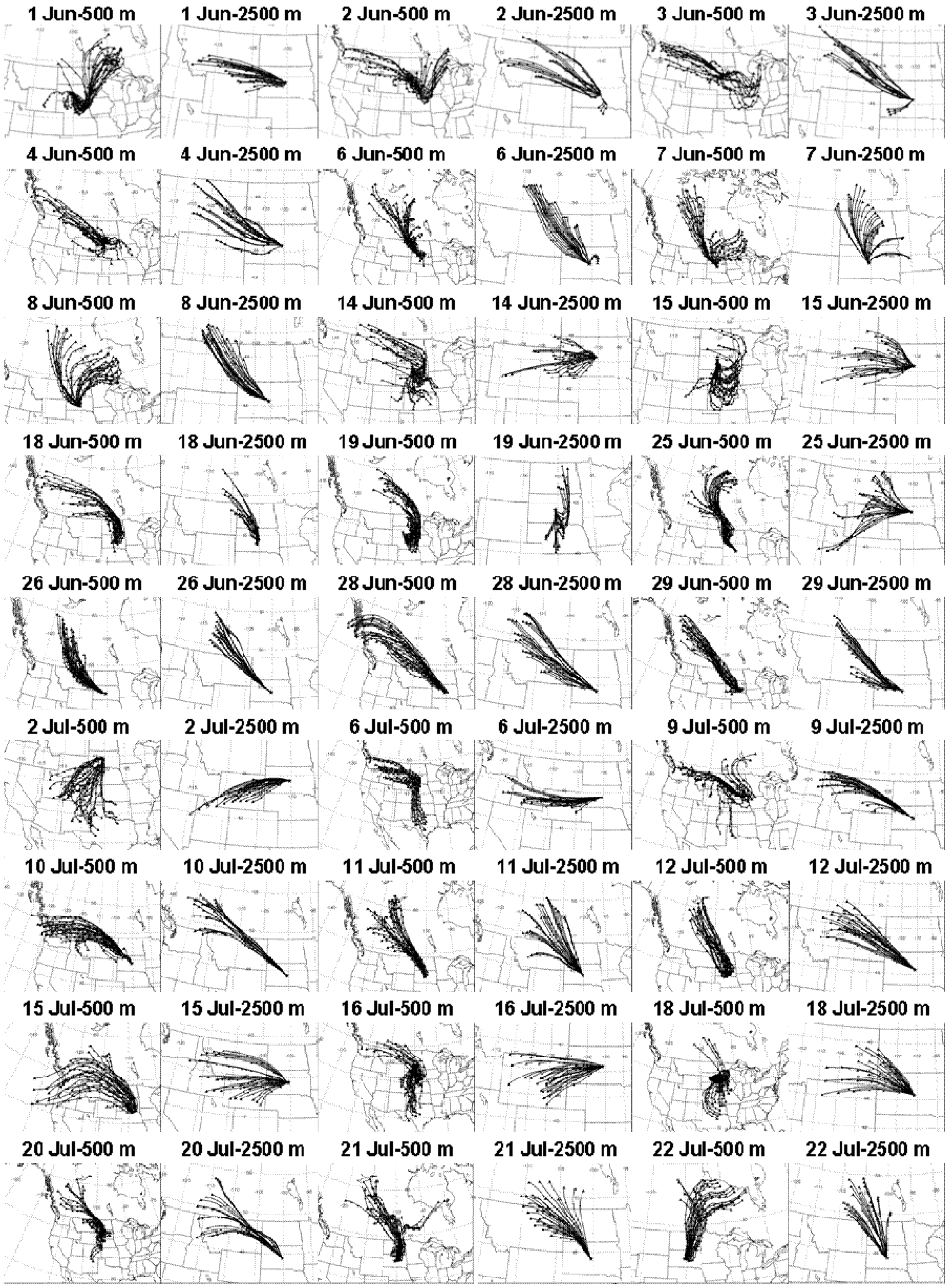
30 May-500 m
30 May-2500 m


1 Jun-500 m
1 Jun-2500 m
2 Jun-500 m
2 Jun-2500 m
3 Jun-500 m
3 Jun-2500 m
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4 Jun-2500 m
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6 Jun-2500 m
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8 Jun-2500 m
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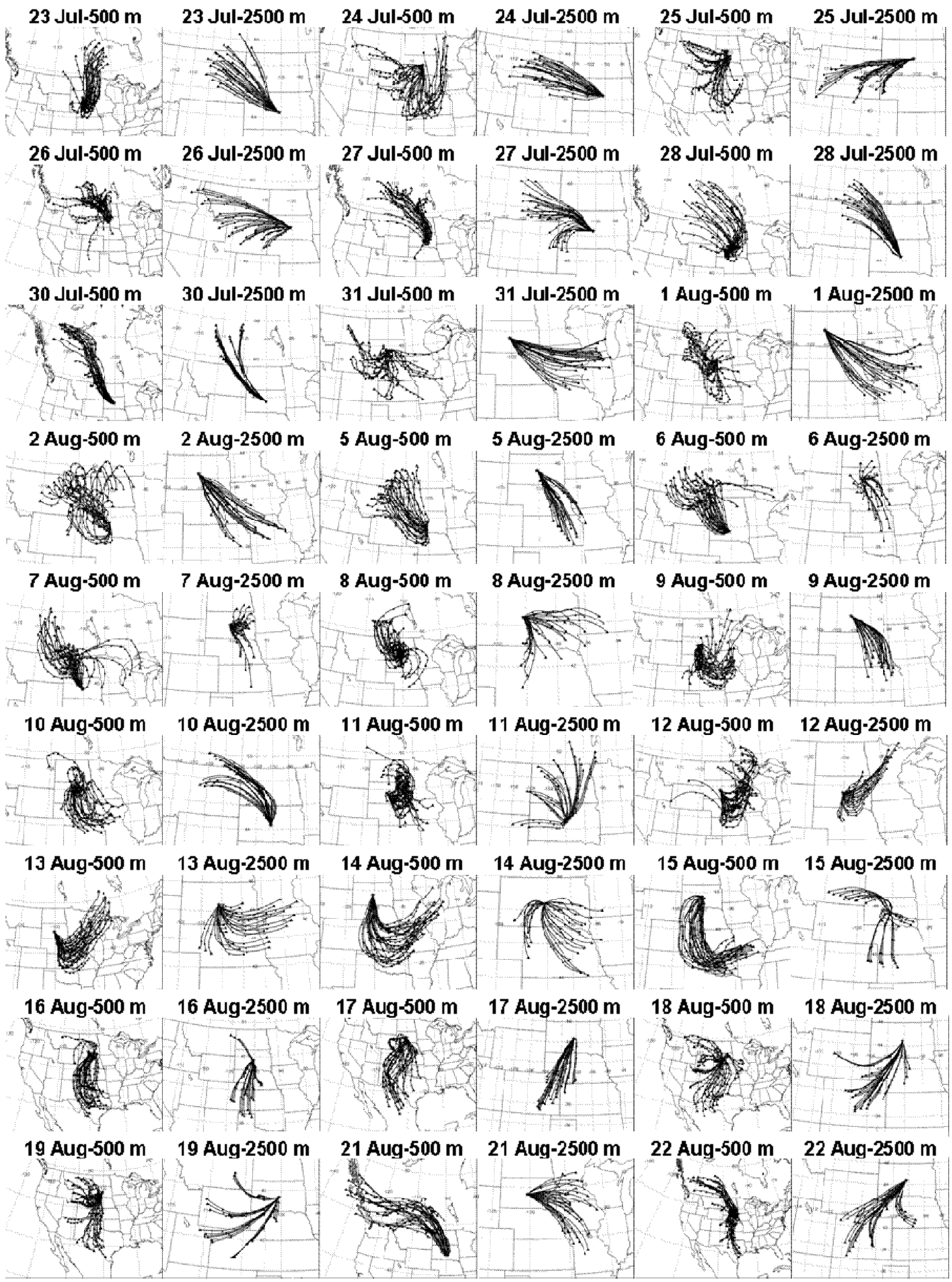
22 Jul-500 m
22 Jul-2500 m


23 Jul-500 m
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22 Aug-2500 m

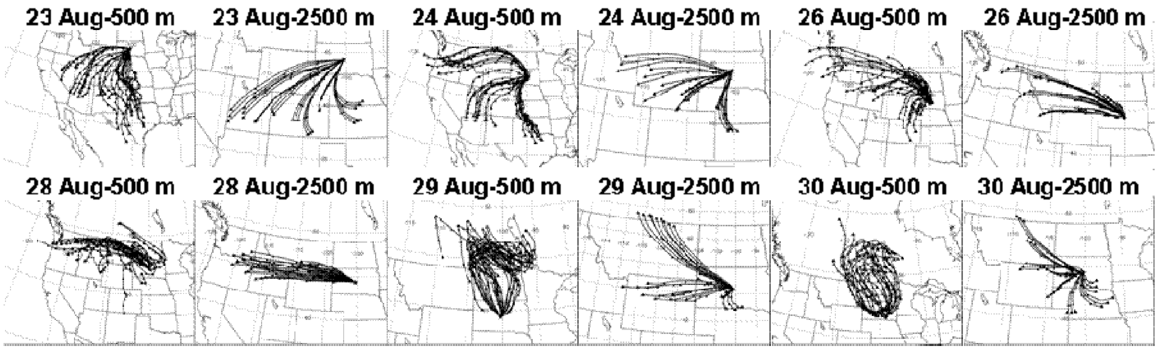

Fig. 23. HYSPLIT backward trajectory ensembles from non-severe weather episode days in South Dakota from 1 May-30 August, 2003. End points 500 m AGL and 2500 m AGL over Pierre (KPIR).

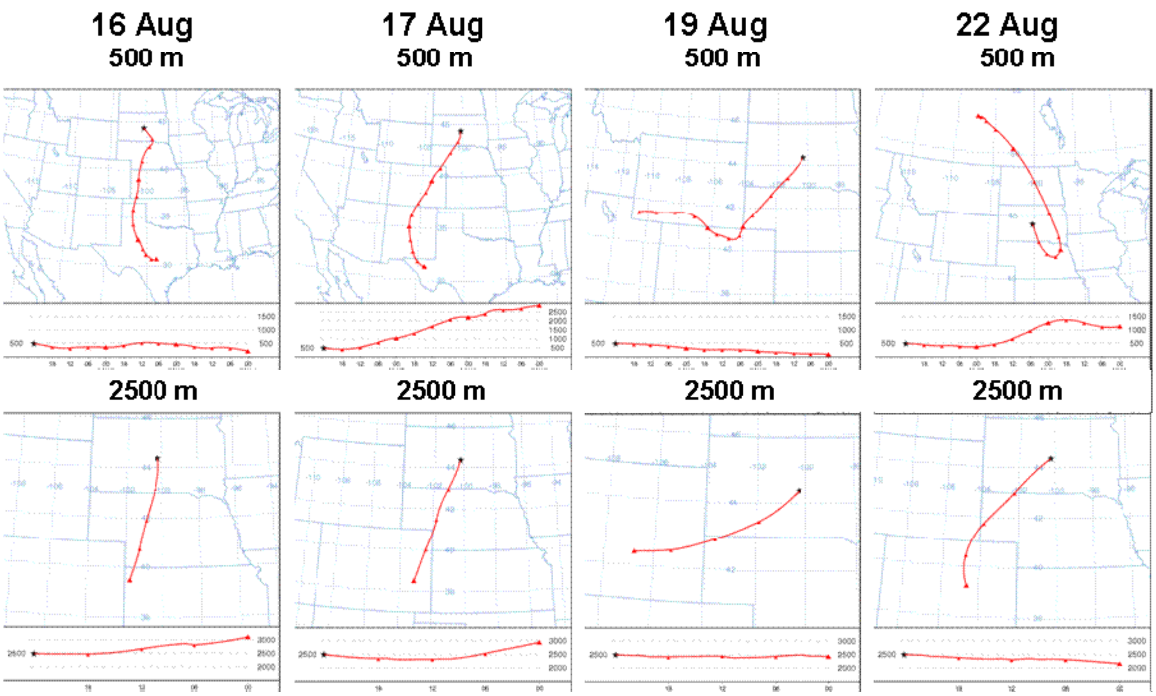

Fig. 24. HYSPLIT backward trajectories from August, 2003. End points 500 m AGL and 2500 m AGL.

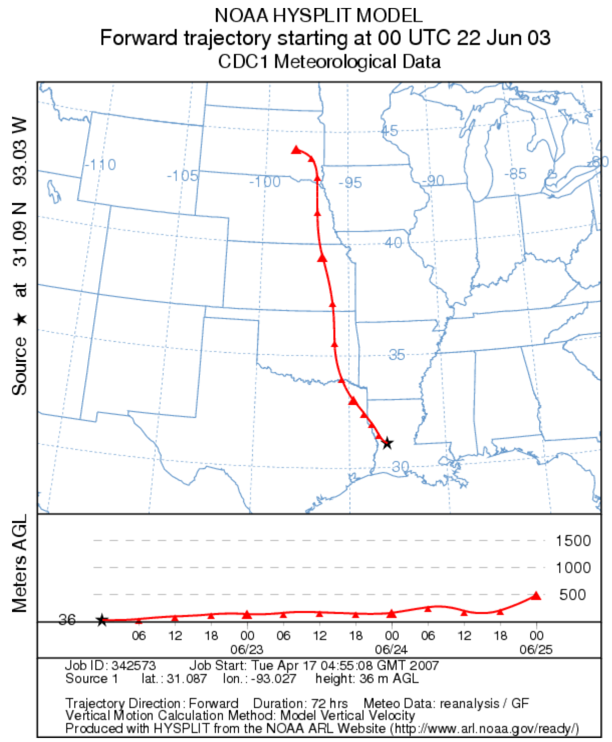

Fig. 25. Same as Fig. 14, except 72 h forward trajectory from starting point at 36 m AGL in Louisiana at 0000 UTC 22 June 2003.

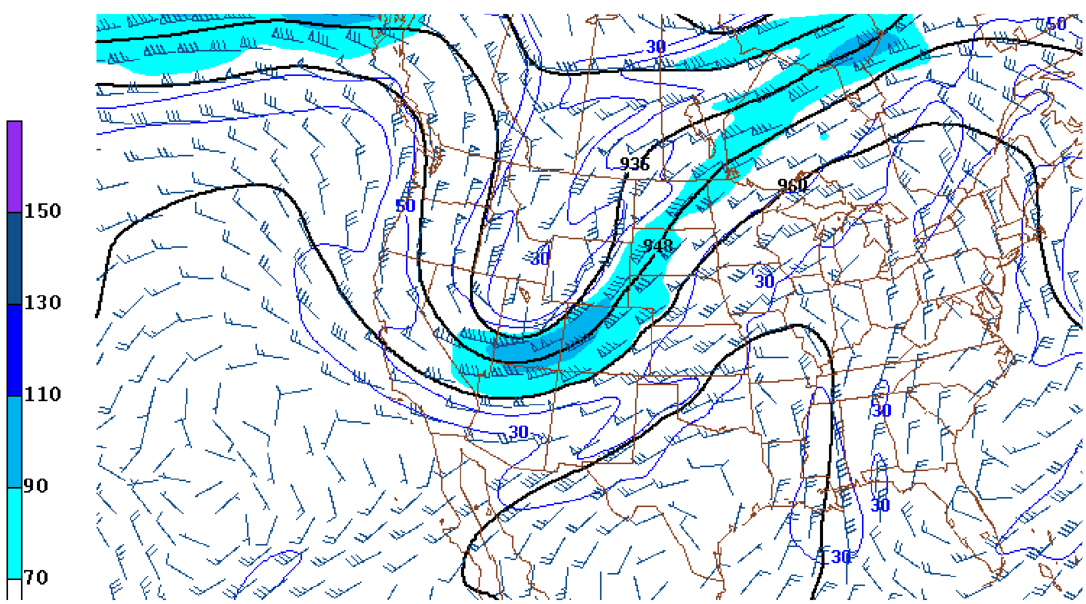

Fig. 26. 300 hPa analysis of heights, isotachs, and winds (kt) at 1200 UTC (NCEP).

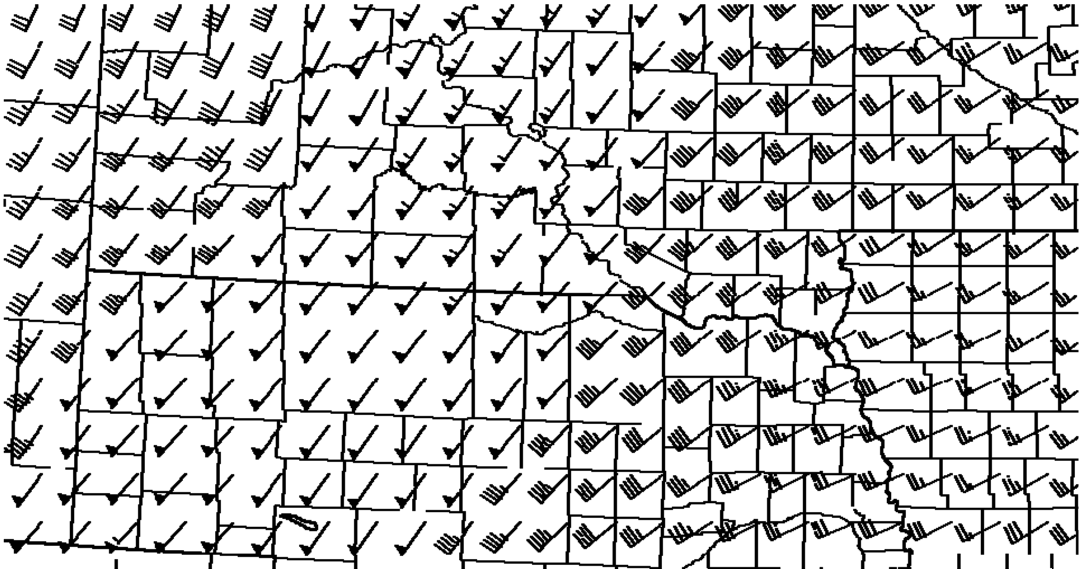

Fig. 27. 2200 UTC RUC 500 hPa 1-Hour forecast (Barker, 2003).

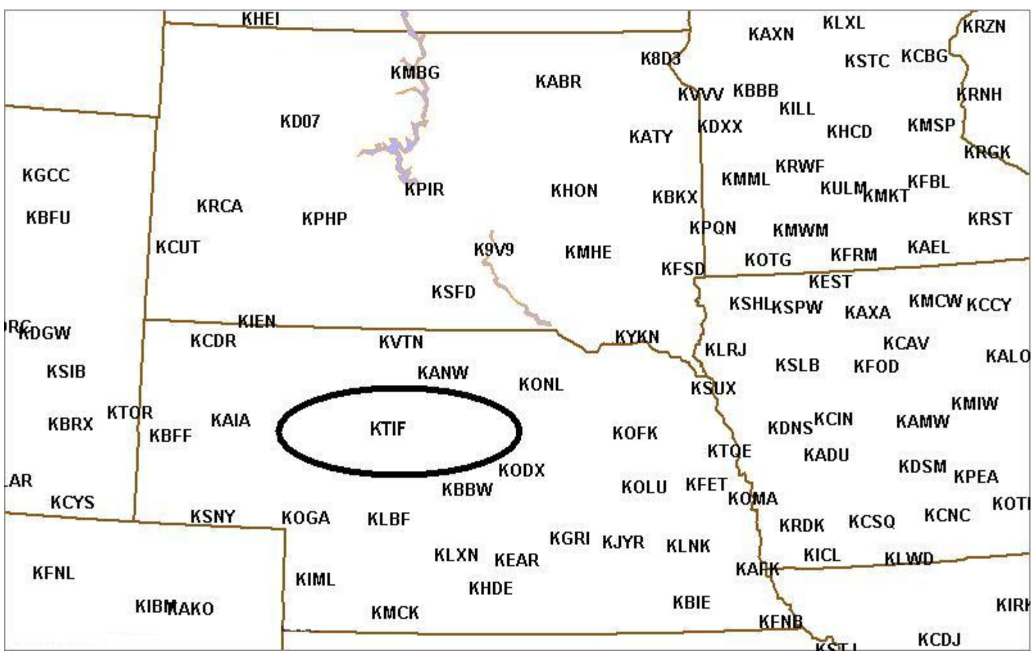

Fig. 28. Surface observation reporting stations in the Northern Plains. Oval indicates area of data void in 2003. A sensor has since been installed at KTIF-Thedford, NE.

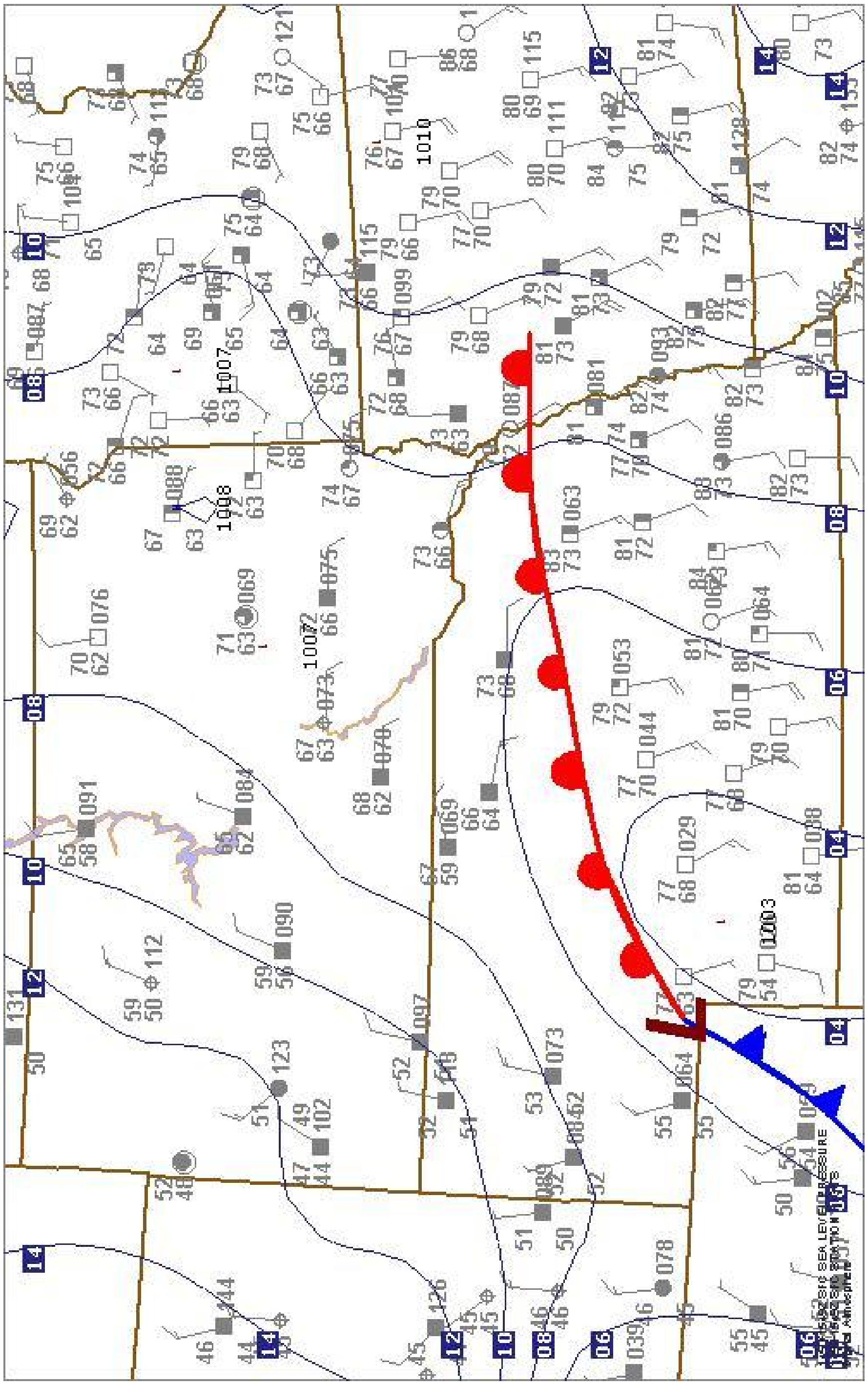

Fig. 29. Subjective hand analysis of surface features at 1500 UTC on 24 June 2003. Isobar fields analyzed using Barnes method and plotted with Digital Atmosphere software program.

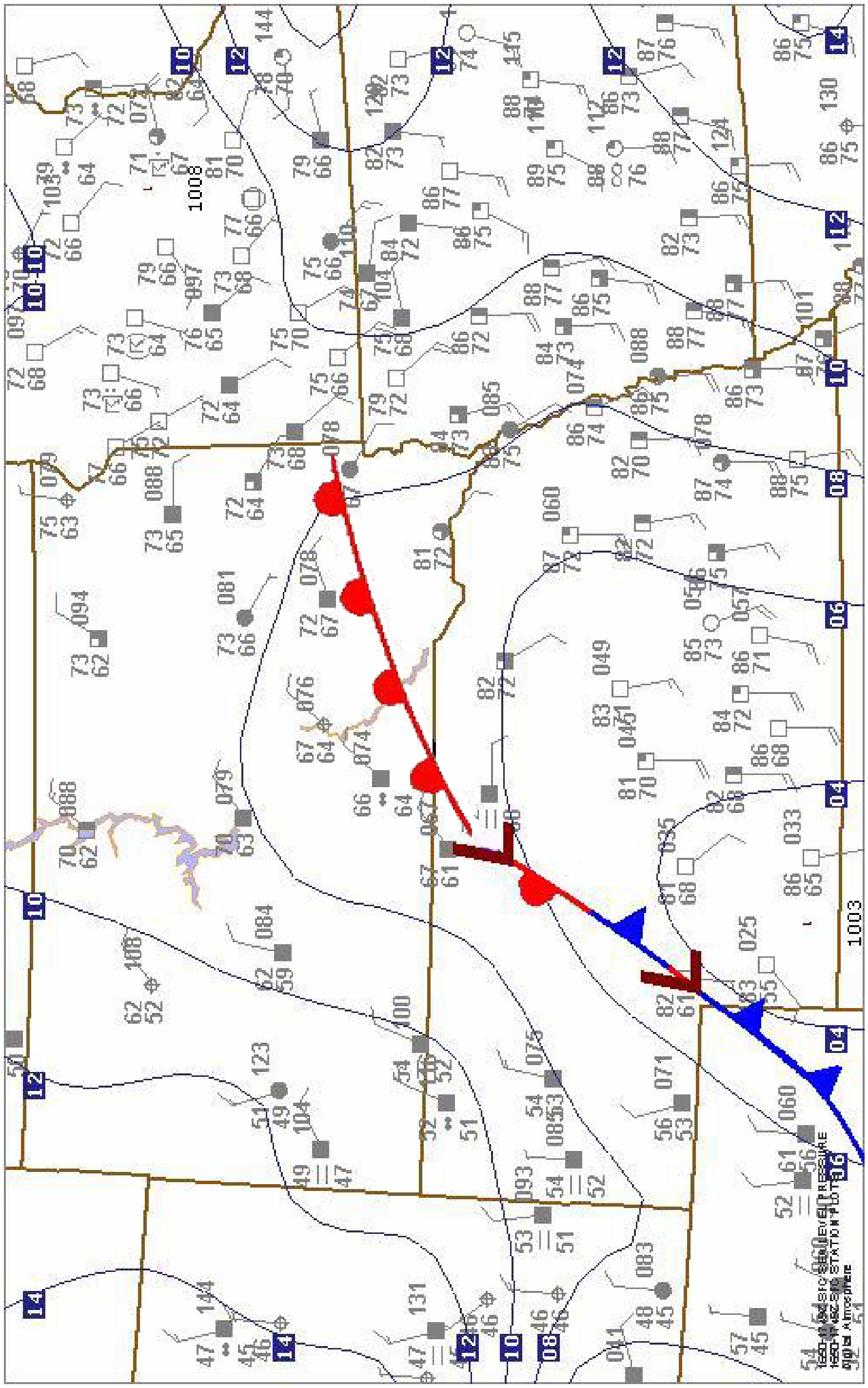

Fig. 30. Same as Fig. 29, except 1700 UTC on 24 June 2003.

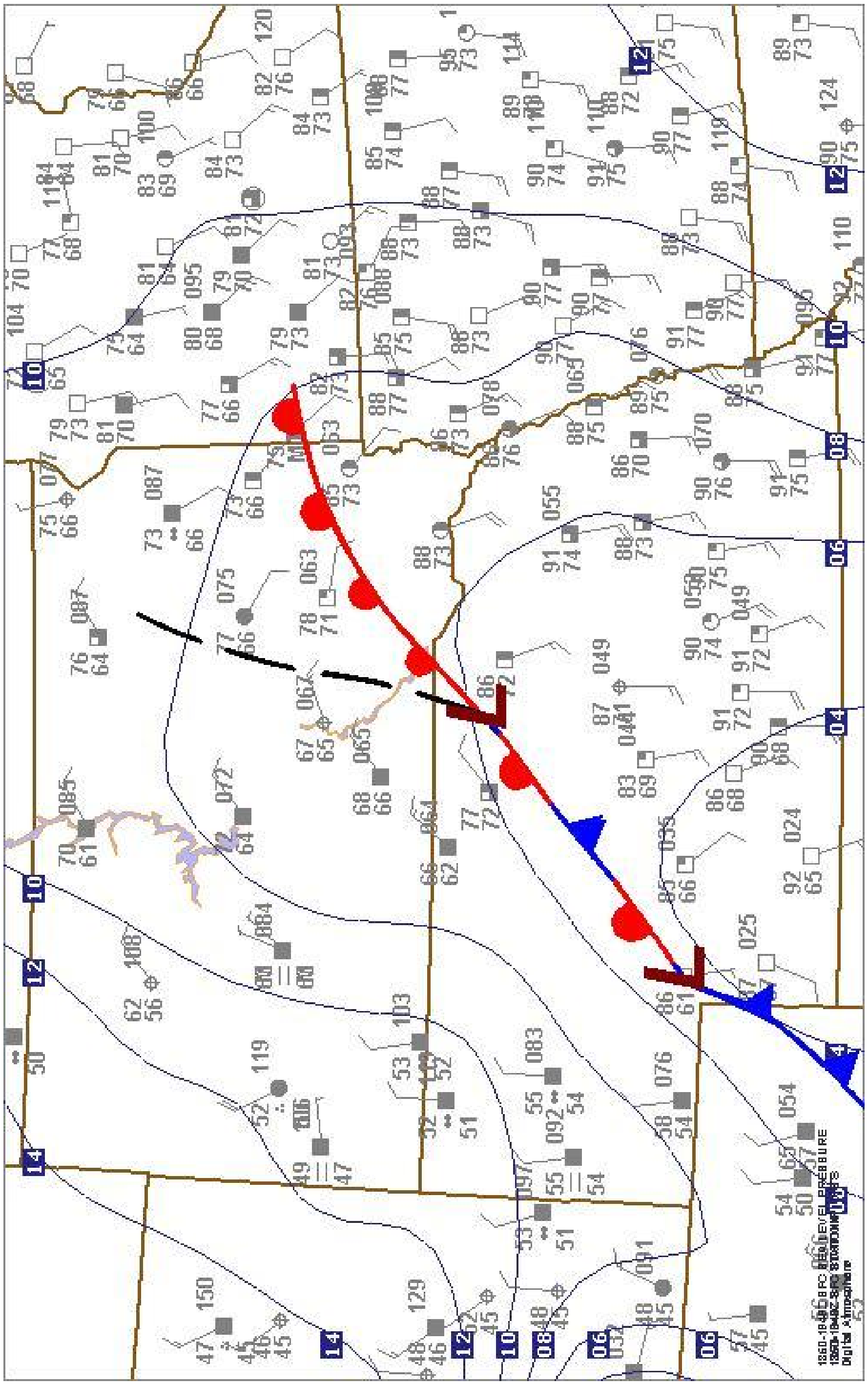

Fig. 31. Same as Fig. 29, except 1900 UTC on 24 June 2003.

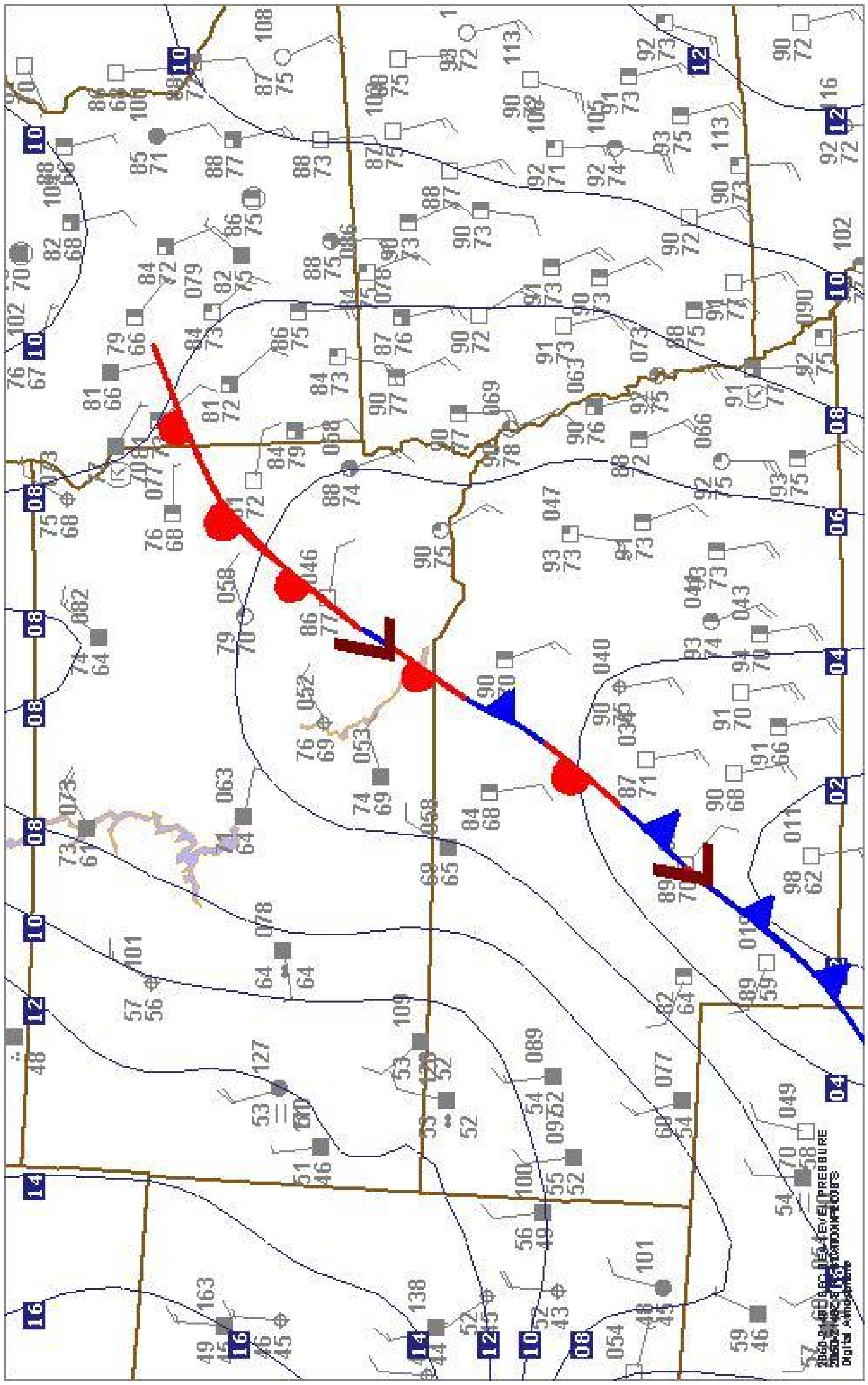

Fig. 32. Same as Fig. 29, except 2100 UTC on 24 June 2003.

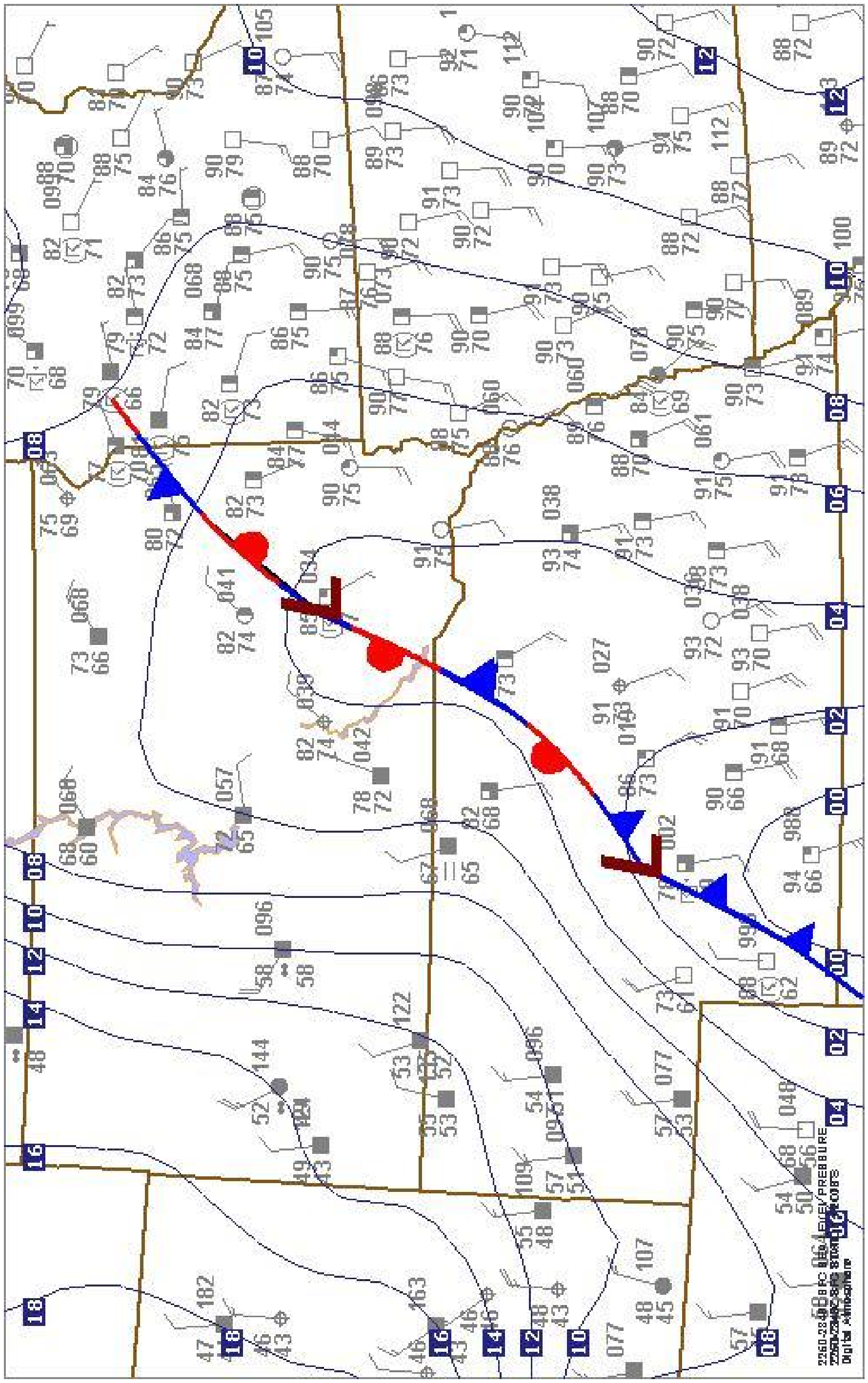

Fig. 33. Same as Fig. 29, except 2300 UTC on 24 June 2003.

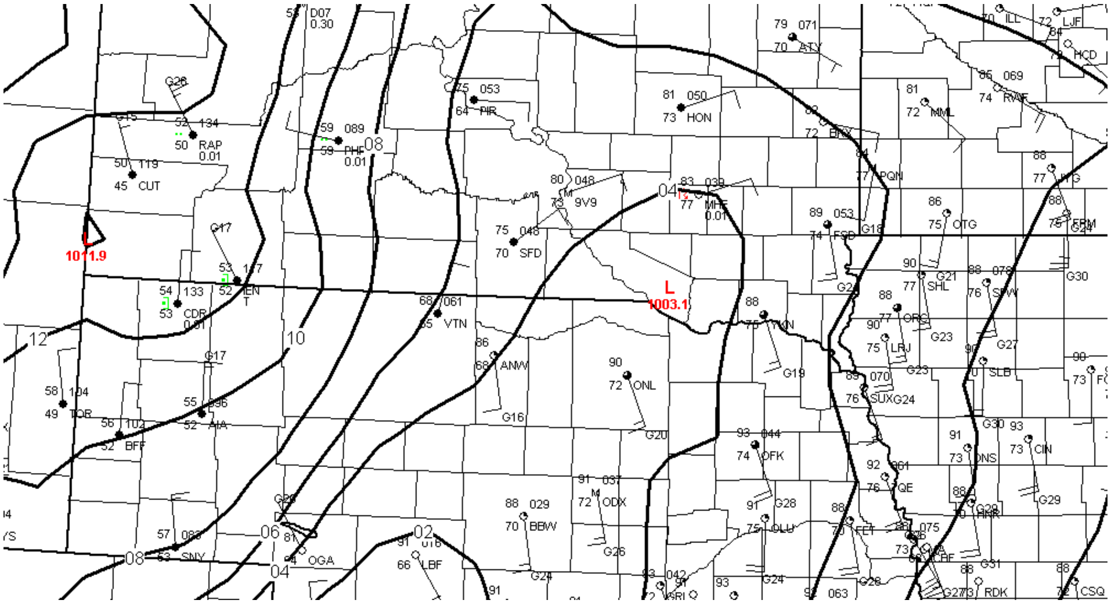

Fig. 34. 2200 UTC hourly observations with RUC 1-Hour pressure contours modified by surface observations (Barker, 2003).

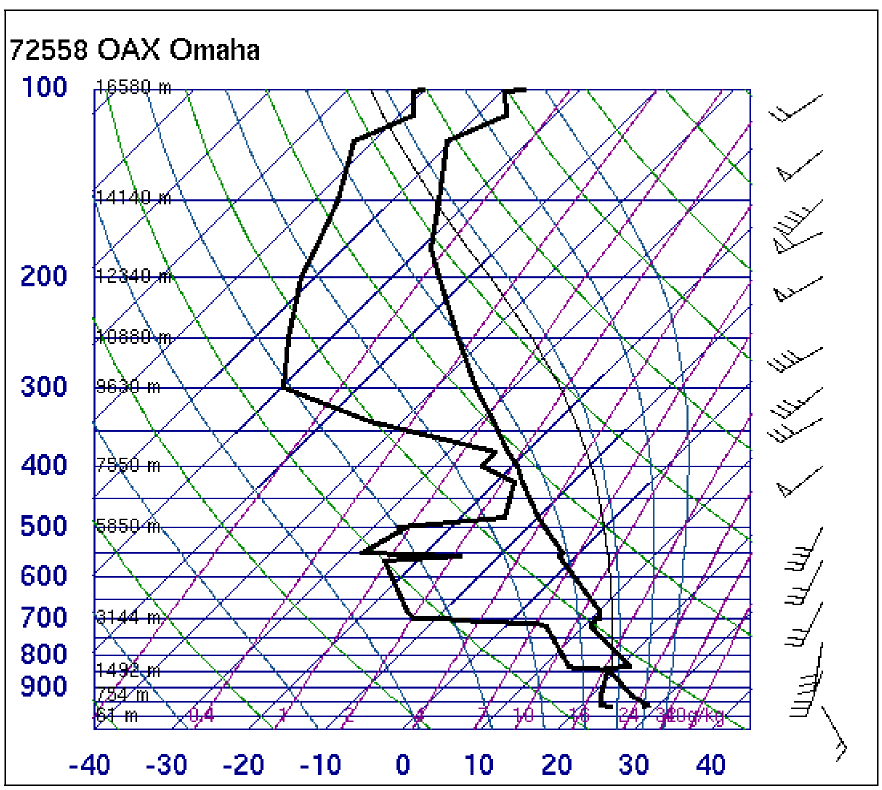

Fig. 35. Omaha, Nebraska (OAX) sounding at 1800 UTC 24 June 2003 (from University of Wyoming online at http://weather.uwyo.edu/upperair/sounding.html).

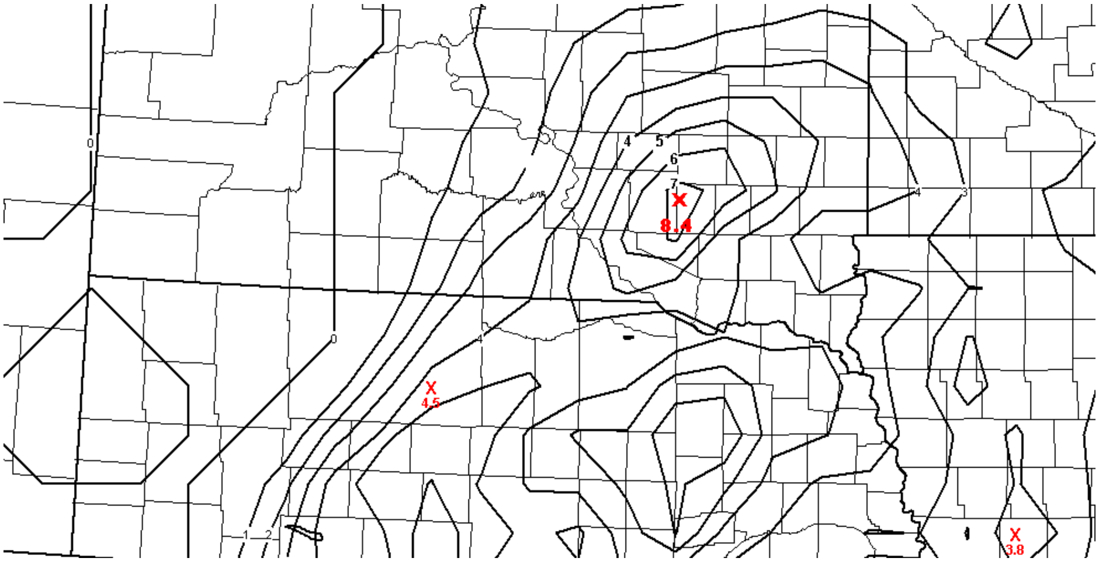

Fig. 36. 2200 UTC RUC 1-Hour forecast 0-1 km Energy-Helicity Index ($EHI_{0\text{-}1}$) (Barker, 2003). Maximum 8.4 near Mitchell (MHE).

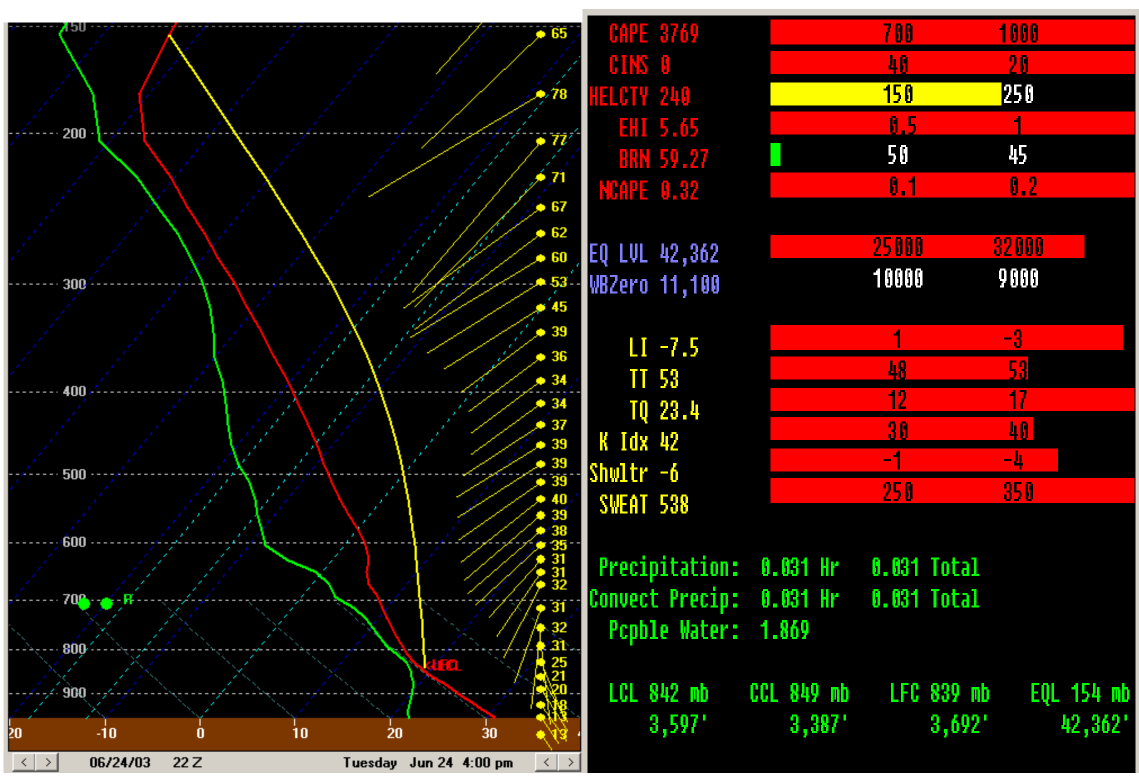

Fig. 37. BUFKIT sounding and severe indices display of 1800 UTC meso-Eta over Mitchell SD (KMHE), valid at 4 pm local time (2100 UTC). On the sounding, green line is dew point, red line is temperature, and yellow line extending from the LFC is CAPE. Derived indices are shown in the right panel.

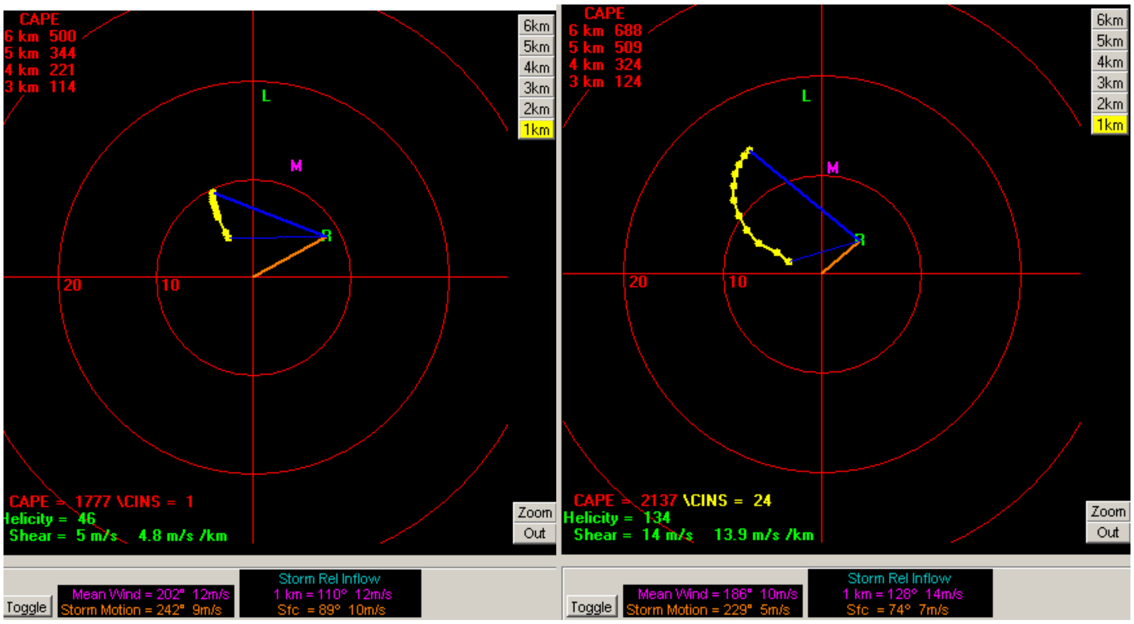

Fig. 38a. 2300 UTC 24 June 2003 and **Fig. 38b.** 0100 UTC 25 June 2003 BUFKIT hodograph of virtual sounding over KHON from 1800 UTC Eta forecast.

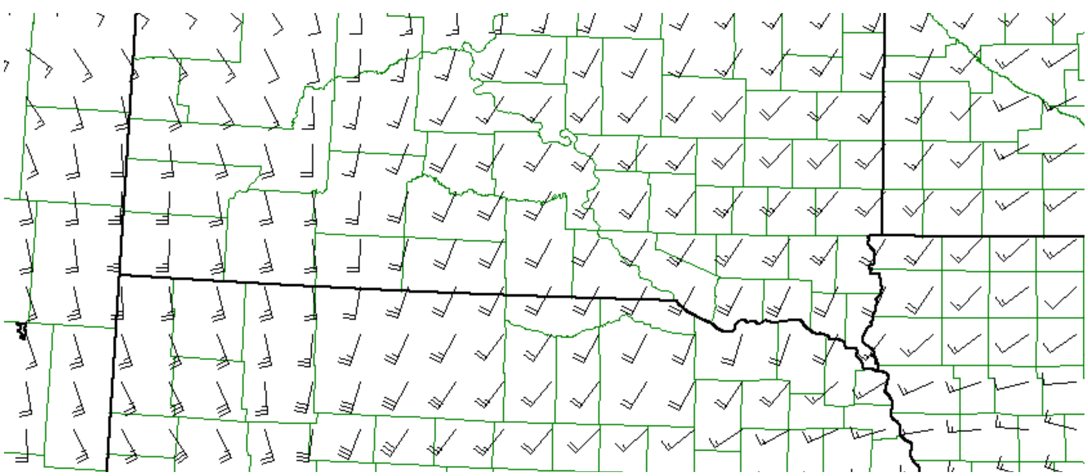

Fig. 39. 24-hour ETA storm relative wind forecast, 5000 m AGL, valid 0000 UTC 25 June 2003.

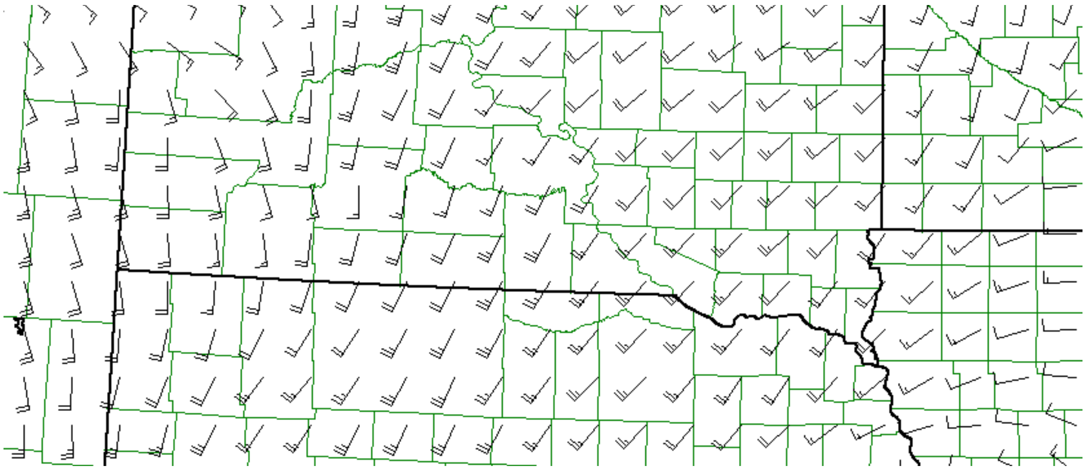

Fig. 40. 12-hour ETA storm relative wind forecast, 5000 m AGL, valid 0000 UTC 25 June 2003.

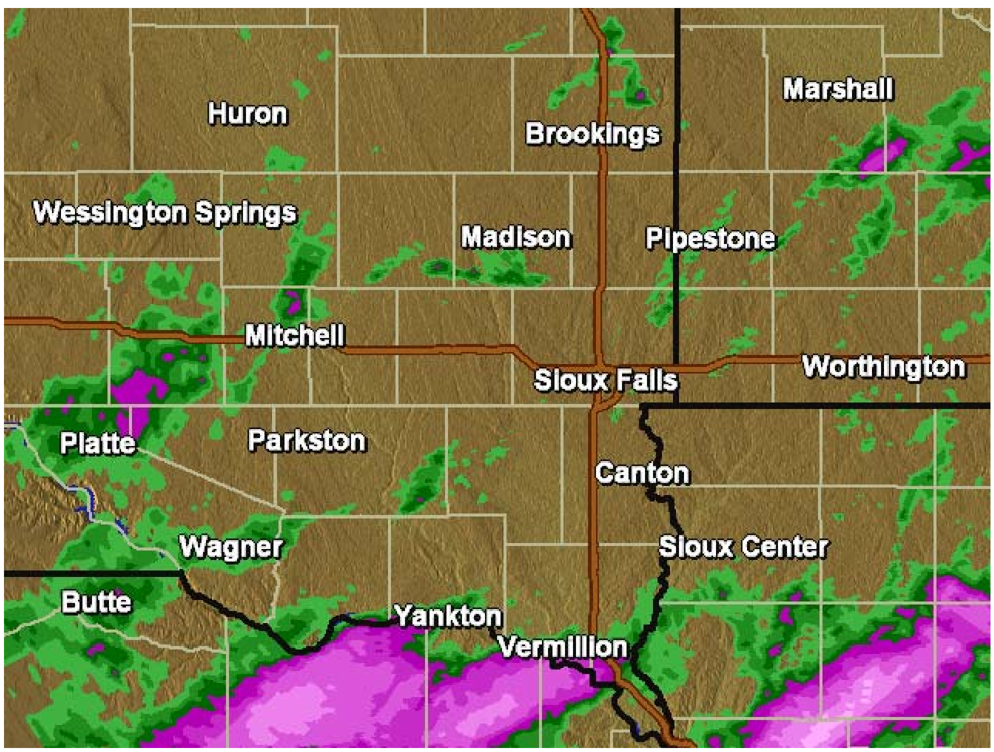

Fig. 41. 1800 UTC Storm total rainfall estimate from FSD WSR-88D radar. Amounts under two inches have been removed. Green colors are amounts above 2.5 inches (51 mm), purple are greater than 4 inches (102 mm), and the maximums in northeast Nebraska and western Iowa are estimated in excess of 6 inches (152 mm) by radar precipitation algorithms.

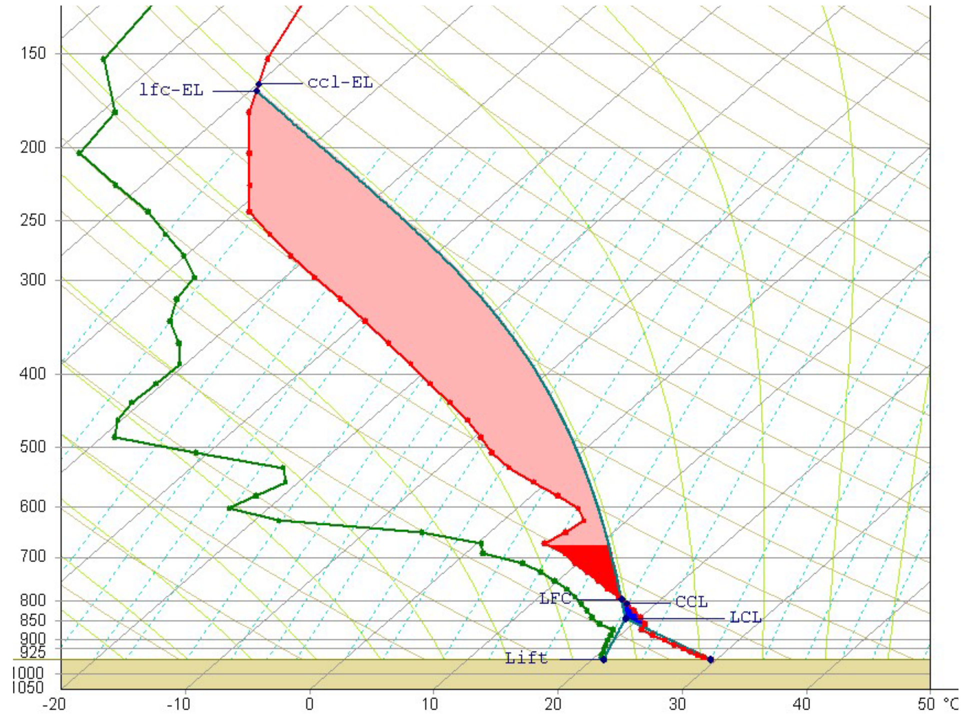

Fig. 42. Virtual sounding skew-t for KMHE valid at 2100 UTC, from 1800 UTC meso-Eta model. Plotted with RAOB software (parameter descriptions available online).

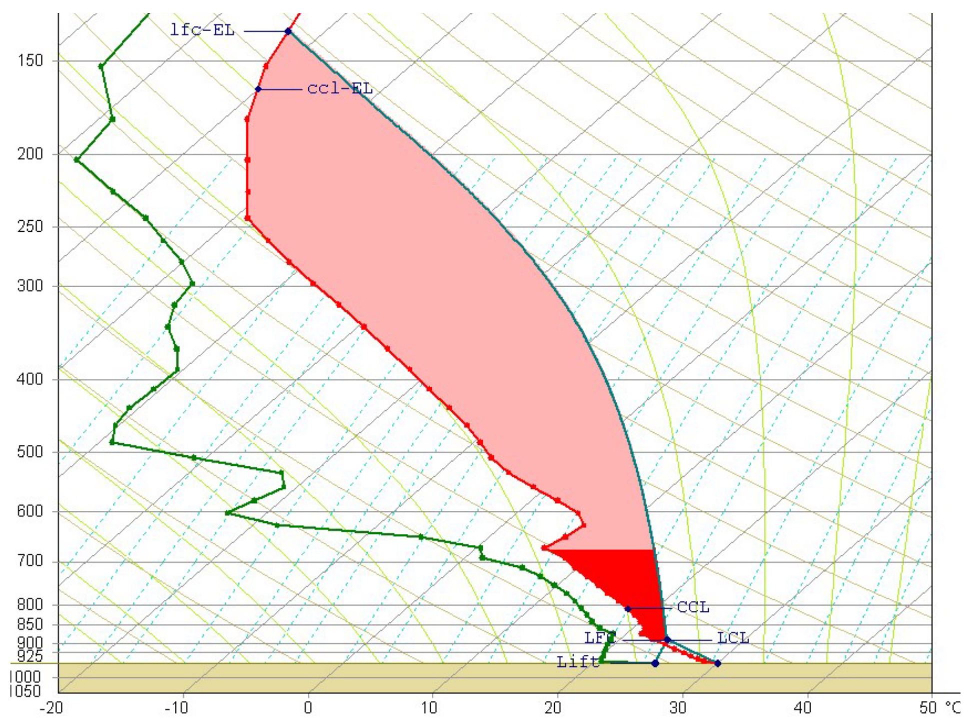

Fig. 43. Virtual sounding skew-t for KMHE valid at 2100 UTC, from 1800 UTC meso-Eta model – except modified for observed surface temperature and dew point.

Fig. 44. Mosaic of .5 degree base reflectivity of WSR-88D radar from Sioux Falls (FSD, in precipitation mode) and Aberdeen (ABR, in clear air mode) at 1728 UTC.

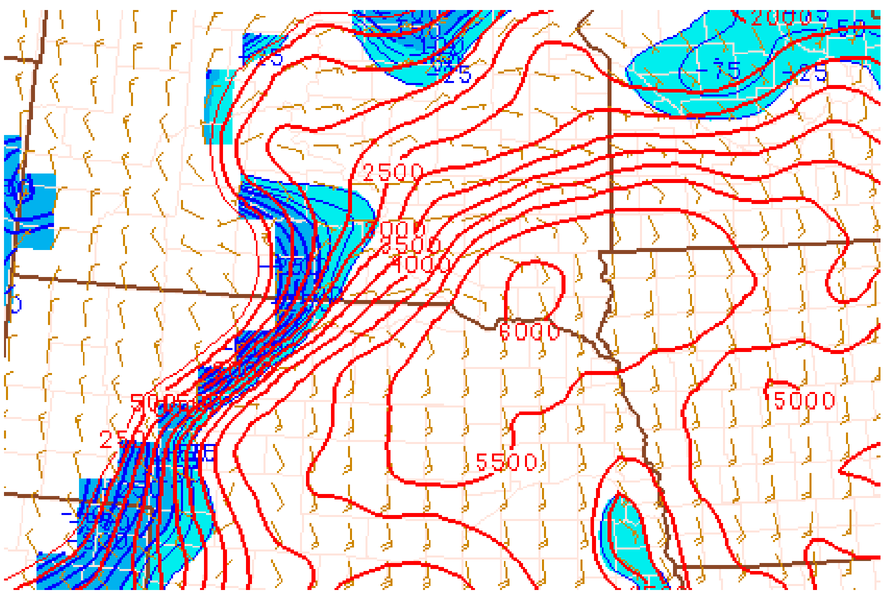

Fig. 45. SPC mesoanalysis 2100 UTC 24 June 2003. Surface based CAPE is in red contours, blue shades are areas of CIN. Real-time SPC mesoanalysis available online at http://spc.noaa.gov/exper/mesoanalysis/.

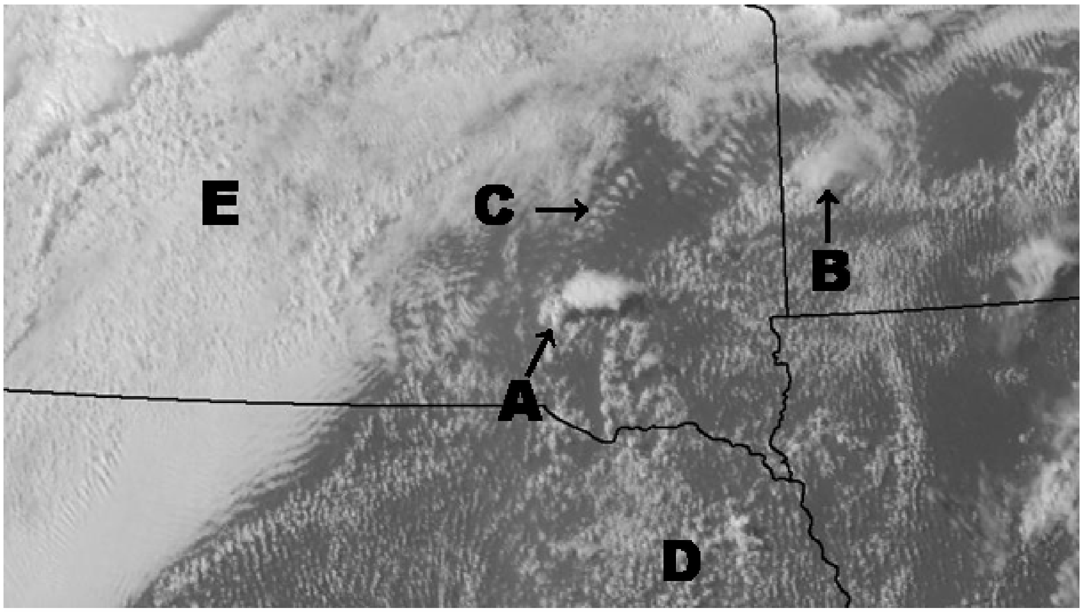

Fig. 46. GOES 1-km visible satellite image, 2115 UTC 24 June 2003. Anvil cloud near Mitchell, SD ("A") is supercell that produced first tornado in SD. Second tornadic supercell in southwest Minnesota ("B"). Both initiated just south and southeast of stable wave clouds ("C"), perpendicular to the southwest wind flow in lower to middle troposphere. Cloud streets northeast Nebraska ("D"), oriented south to north in the low-level winds. Cells on the northern side of the cloud streets would become tornadic as they approached the South Dakota border. Cloud shield covered rest of SD ("E").