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CENTRAL REGION APPLIED RESEARCH PAPERS
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CENTRAL REGION APPLIED RESEARCH PAPERS

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CENTRAL REGION APPLIED RESEARCH PAPER 97-1

WINTER STORM DECEMBER 14-15, 1987 -- WESTERN AND NORTHERN ILLINOIS

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1. Introduction

In 1987, a powerful winter storm blasted portions of Illinois late on December 14th and early on the 15th. The storm was the most intense in northern Illinois since the blizzard of January 13, 1979.

The storm produced a band of very wet, heavy snow ranging in depth from six to 12 inches across portions of western and northern Illinois. The axis of the heaviest snow in Illinois stretched from just west of Chicago to near Rockford and Quincy. The six-inch or greater snowfall accumulation line extended north and west of a line from south suburban Chicago to just west of Springfield to a point about 60 mi north of St. Louis.

At the peak of the storm, during the early morning of the 15th, most of western and northern Illinois experienced a combination of thunderstorms, snow, sleet, some freezing rain and a few cases of hail. Very strong winds also developed during the late night of the 14th and early on the 15th when surface pressures plunged as the storm occluded and moved northward across Illinois.

By 9:00 a.m. local time (15Z) the surface pressure at O'Hare International Airport plummeted to 981 mb (28.95 in.) and established an all time record low pressure for the month of December. Nearby Glenview Naval Air Station recorded a low reading of 979 mb.

2. Synoptic Development

The storm began to organize as a 1004 mb low pressure center over southwest Arkansas on the evening of the 14th which then raced northeast at 50 kts. As the low center turned more northerly to track just west of the southern tip of Illinois by midnight it deepened to 993 mb. The low continued north across Illinois during the late night, intensified explosively, slowed to 20 to 25 kts as the low was located about 60 mi southwest of Chicago by 6:00 a.m. (12Z) on the 15th.

In the six hours between midnight and 6:00 a.m. on the 15th the pressure at O'Hare dropped at an extreme rate to 984 mb. This was a total six-hour fall of

24.3 mb, or nearly 3/4 of an inch of mercury (see the barograph trace for WSFO Chicago, Figure 1). The low was located just west of Alpena in northern lower Michigan by 6:00 p.m. (00Z) on the 15th.

3. Special Storm Features

There were many interesting, unusual, and unique features of this storm. These included:

(1) An extremely rapid intensification of the storm occurred as it moved north across Illinois during the late night. Sustained winds of 40 to 50 mph with gusts up to 60 to 70 mph were accompanied by widespread embedded thunderstorms over areas that were also receiving heavy snow, sleet and hail (3/4 in. hail was reported at Joliet in northeast Illinois). The thunderstorm activity was of an unusually long duration for a winter storm of this nature (a number of official Weather Service locations in northern and western Illinois observed occasional thunder over a two to four hour time period).

(2) Extremely strong upper air dynamics caused the surface low to occlude and deepen rapidly as it pushed into northern Illinois, which resulted in the warmer air initially to the southeast of the low center being shunted to the east of the storm over Indiana. The occlusion process set up some unique conditions which allowed precipitation to remain mainly snow, or a mixture of snow and sleet, near and along the actual storm center's path over northeast Illinois (not the typical situation where a rain-snow line extends well back to the northwest of a northeastward bound low center).

(3) A vigorous 500 mb short wave moving out of the south central Plains on the evening of the 14th became a closed 500 mb low that moved over Chicago on the morning of the 15th (the heaviest snow over Illinois was nearly coincidental with the closed circulation at 500 mb. Maximum vorticity values at 12Z on the 15th were analyzed with extreme values of 36 x 10^{-5} sec^{-1} analyzed just to the south of Springfield. The paths of the surface, 850, 700, and 500 mb lows all moved northeast to near or over Chicago early on the 15th and the associated speed maxima or jet south of the 500 mb low/trough ranged from 100 to 125 kts during the 48 hours leading up to and including the period of the storm (14/1200Z-16/0000Z).

(4) The December 14-15th storm showed an interesting center that was very "tightly wound" with very strong pressure gradients. The associated winds and pressure drops were akin to that of an approaching tropical storm or minimal hurricane. This seemed to be especially true when the system reached its peak intensity as it approached Chicago. In the vicinity of Chicago, winds before the center's arrival were frequently gusting above 50 mph and sometimes reached 60 to 70 mph. Thunderstorms with snow, sleet, and some hail were widespread across northern Illinois and lasted on and off for up to a few hours prior to the storm center's arrival. As the center moved overhead, winds suddenly became light or calm and skies became partly cloudy in places. Winds shifted and wind speeds and pressures increased sharply as the low pushed northeast away from the area (thunderstorms ended after the center passed off to the northeast).

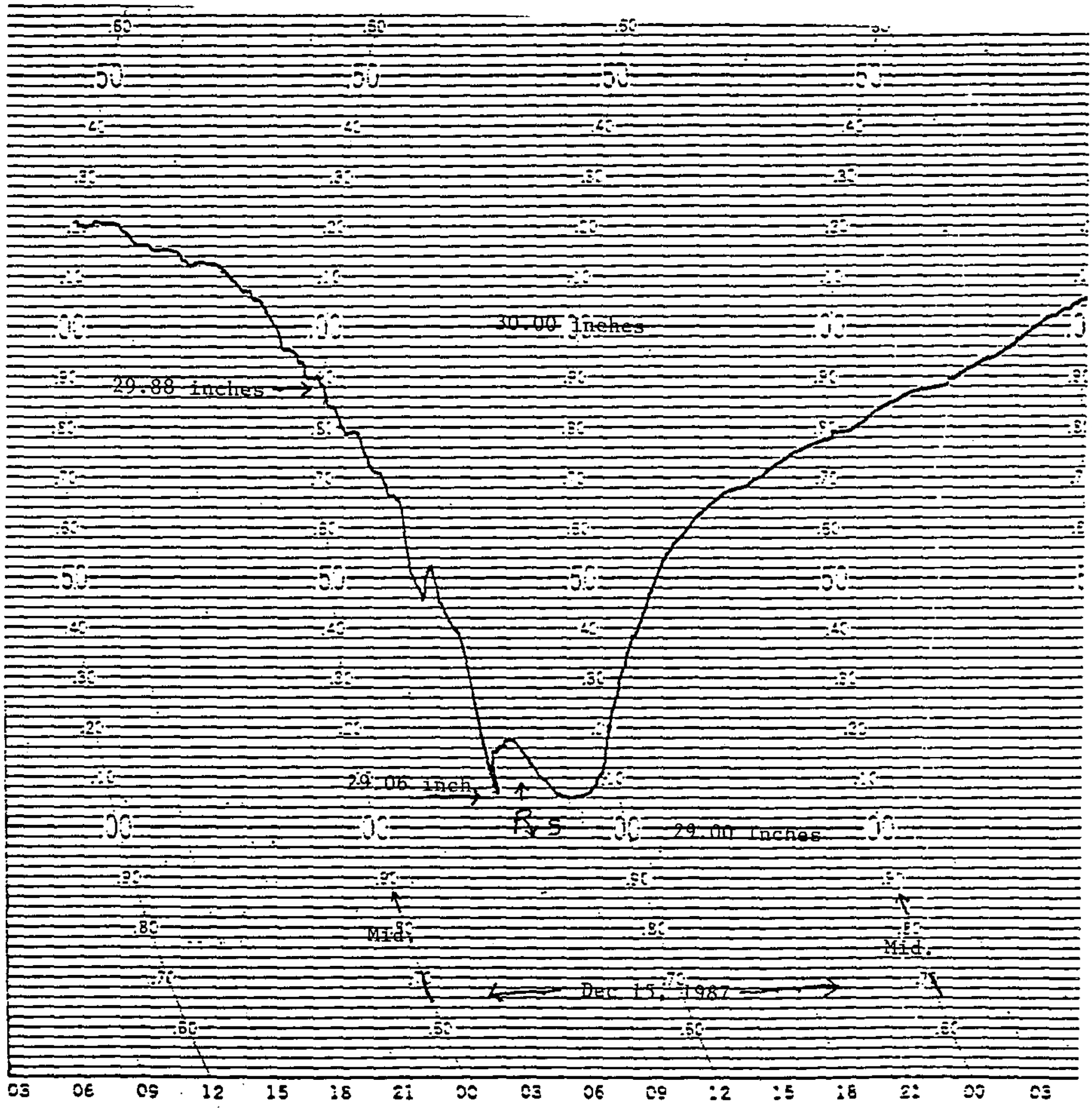

Figure 1 Barograph trace WSFO Chicago, Illinois (2 N WSO ORD). Pressure and time correlations to above chart not applied.

4. Performance Characteristics of the NGM Model - A Comparison of the NGM Model with Observed Conditions

The Nested Grid Model (NGM) model output for 12, 24, 36, and 48 hour forecasts charts were used for determining expected paths of the 500 mb, 850 mb, and surface low centers. These projected paths were compared to the observed low pressure center paths. Special emphasis was placed on the time frame around 15/1200Z during which was the critical period that the storm affected Illinois. NGM features of importance over Illinois or within proximity of 400 n mi proximity of Illinois were evaluated in two steps beginning with the initial 13/1200Z NGM run and ending with the 15/0000Z run.

First, the actual storm center movements for the 500 mb, 850 mb, and surface levels were plotted on a standard weather plotting chart at 12 hour intervals, for the 48 hour period prior to 15/1200Z (the time of the peak intensity of the storm to affect Illinois). Surface low pressure center positions were plotted every hour as it moved through Illinois.

Secondly, the observed storm center location points were connected by a line that closely approximated the storm's actual path. Next, NGM 12, 24, 36, and 48 hour progged low center positions were plotted on the same weather plotting chart and the points were connected. Finally, the 12, 24, 36, and 48 hour NGM predicted paths were compared to the storm's actual path.

Comparisons were made only for that segment of the path that directly crossed Illinois. The comparison of the storm's low center path consisted of the "track's closest approach" and "average distance between tracks, using NGM paths versus observed paths. Comparisons of the NGM and observed paths were made for four different NGM initial runs, beginning with the 13/1200Z run and ending with the 15/0000Z run.

At the peak of storm intensity over Illinois, low center point to point location and intensity comparisons were made for 15/1200Z (NGM forecast low center position locations and intensity at 15/1200Z versus the observed location and intensity). In a similar manner, the NGM 850 mb temperature forecast over northern and western Illinois were compared to observed 850 mb temperatures for 15/1200Z.

The table below summarizes the results of the above discussion while Figures 2-5 graphically depict these comparisons.

TABLE 1
Comparisons of NGM to Observed Conditions

NGM Run-Time	CA	X	PP	I	TT8
13/1200Z (LT 48 hours)					
500 mb	-	-	210 W	+3	-
850 mb	-	-	140 NW	+7	-
SFC	100 + (NW)	110 + (NW)	120 W	+17	-
14/1200Z (LT 36 hours)					
500 mb	120 + (NW)	140 + (NW)	200 WNW	+3	
850 mb	40 + (NW)	90 + (NW)	90 WNW	+4	+4 to +7
SFC	25 + (NW)	40 + (NW)	120 SW	+12	
14/1200Z (LT 24 hours)					
500 mb	30 + (NW)	90 + (NW)	120 SW	+8	
850 mb	10 + (NW)	C/O	0	+2	-1 to +3
SFC	10 - (E)	40 - (E)	90 SSE	+9	
15/0000Z (LT 12 hours)					
500 mb	10 + (NW)	25 + (NW)	90 SW	+8	
850 mb	5 - (SE)	10 - (SE)	35 NE	+3	-2 to +2
SFC	75 - (SE)	85 - (SE)	100 SSE	+10	

(NOTE: CA, X, PP measured in nautical miles (n mi); I - Intensity for 500 mb and 850 mb in decameters (dm) and for SFC in millibars (mb); TT8 - Temp 850 mb in degrees Celsius (C). Deviation of NGM path from observed (+) Left...(-) Right.

Definition of Terms:

CA "Track's Closest Approach" - Comparison of the closest approach of the NGM's forecast low center's path (500 mb, 850 mb, SFC) to the actual path (comparison made only for the Illinois portion of the low center's path). Closest approach measured by taking a line normal to the NGM's path and projecting the line to a point where the line was closest to that of the observed low center's path (time-distance relationships were not made - only the paths were compared). In the event the tracks of the NGM forecast path crossed over the observed path, reference is made as to "cross over" (C/O). "Looking" downstream along the storm's observed

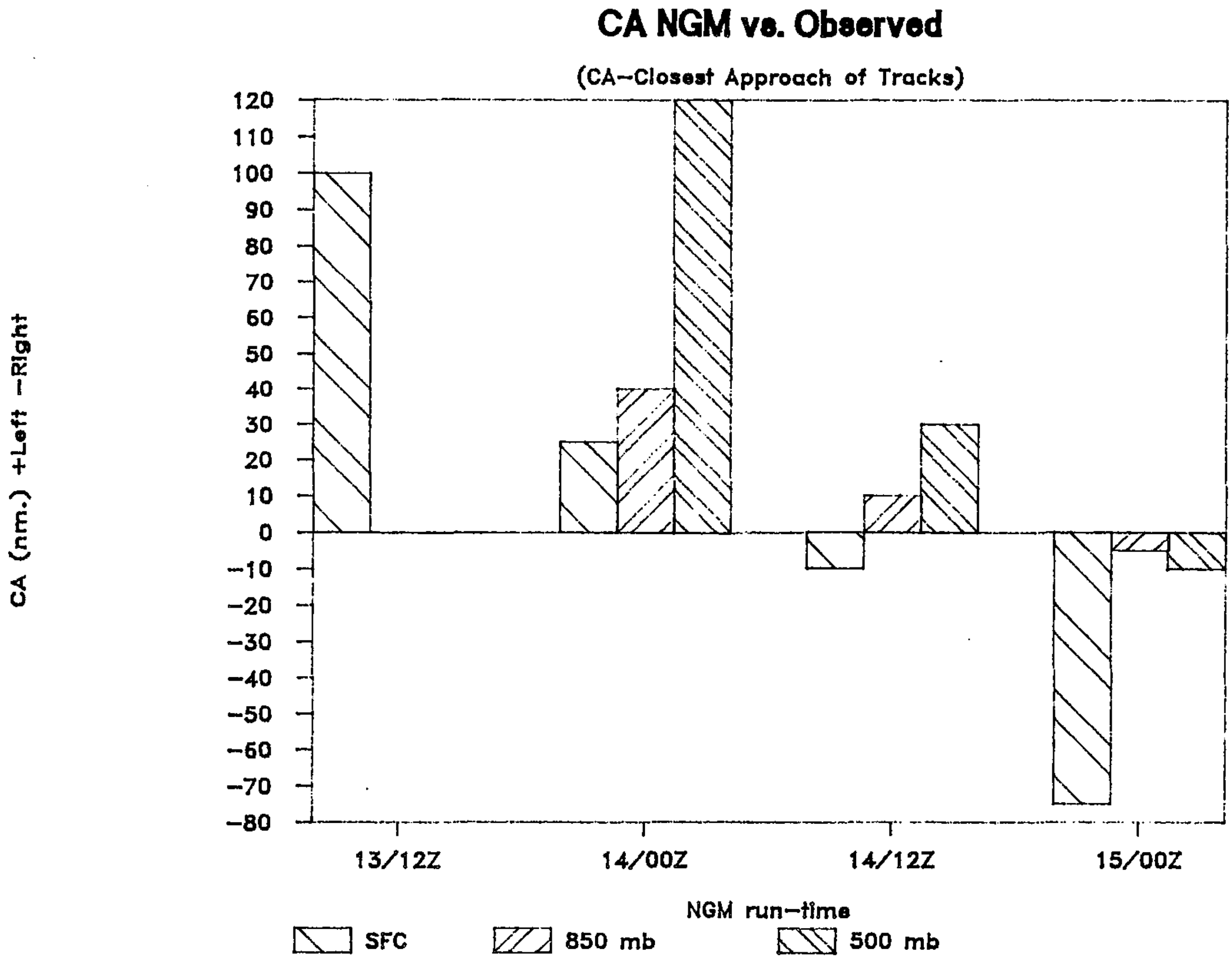

Figure 2 Closest approach of NGM forecast track compared to observed track.

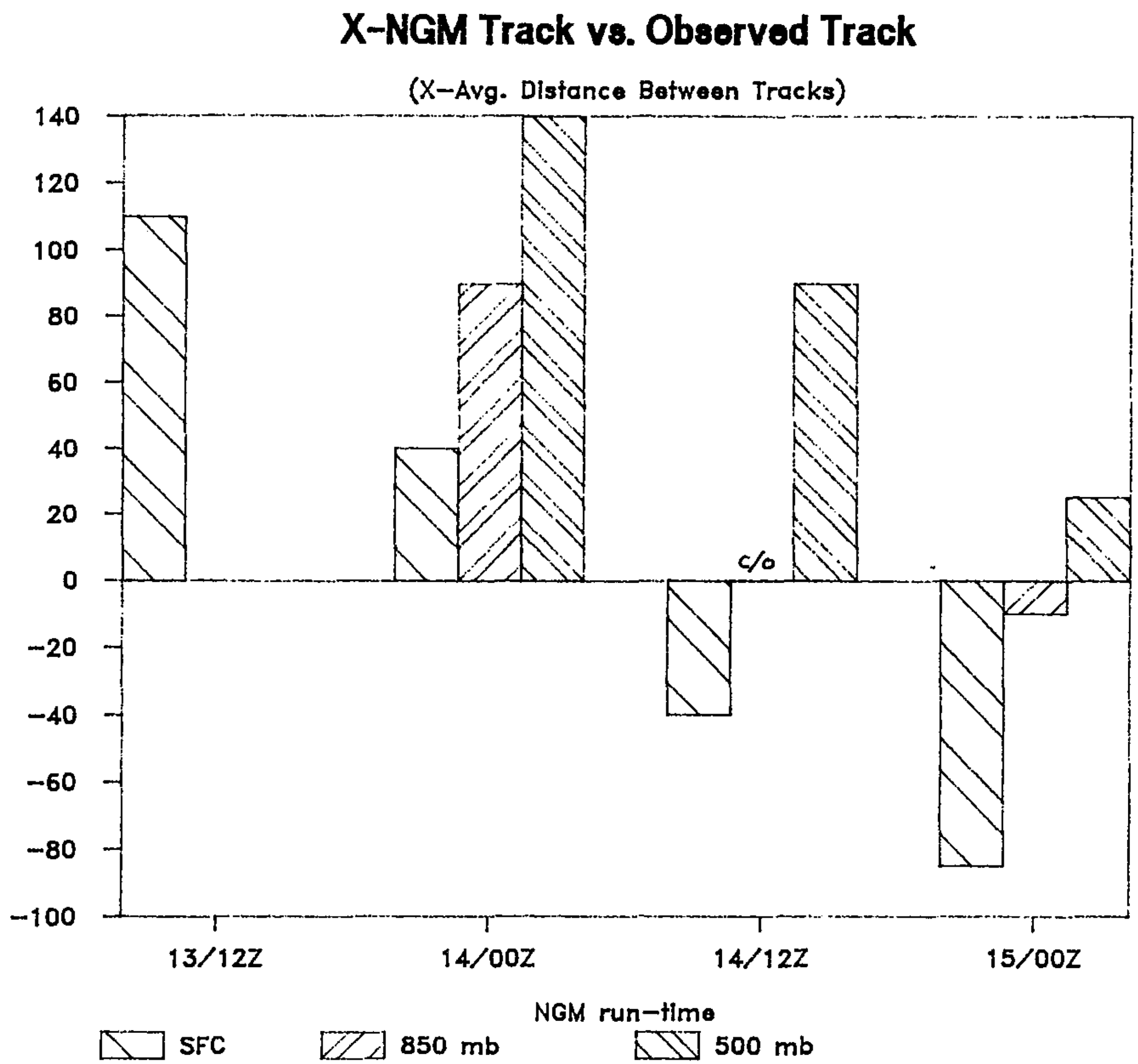

Figure 3 Average distance between observed and NGM forecast track.

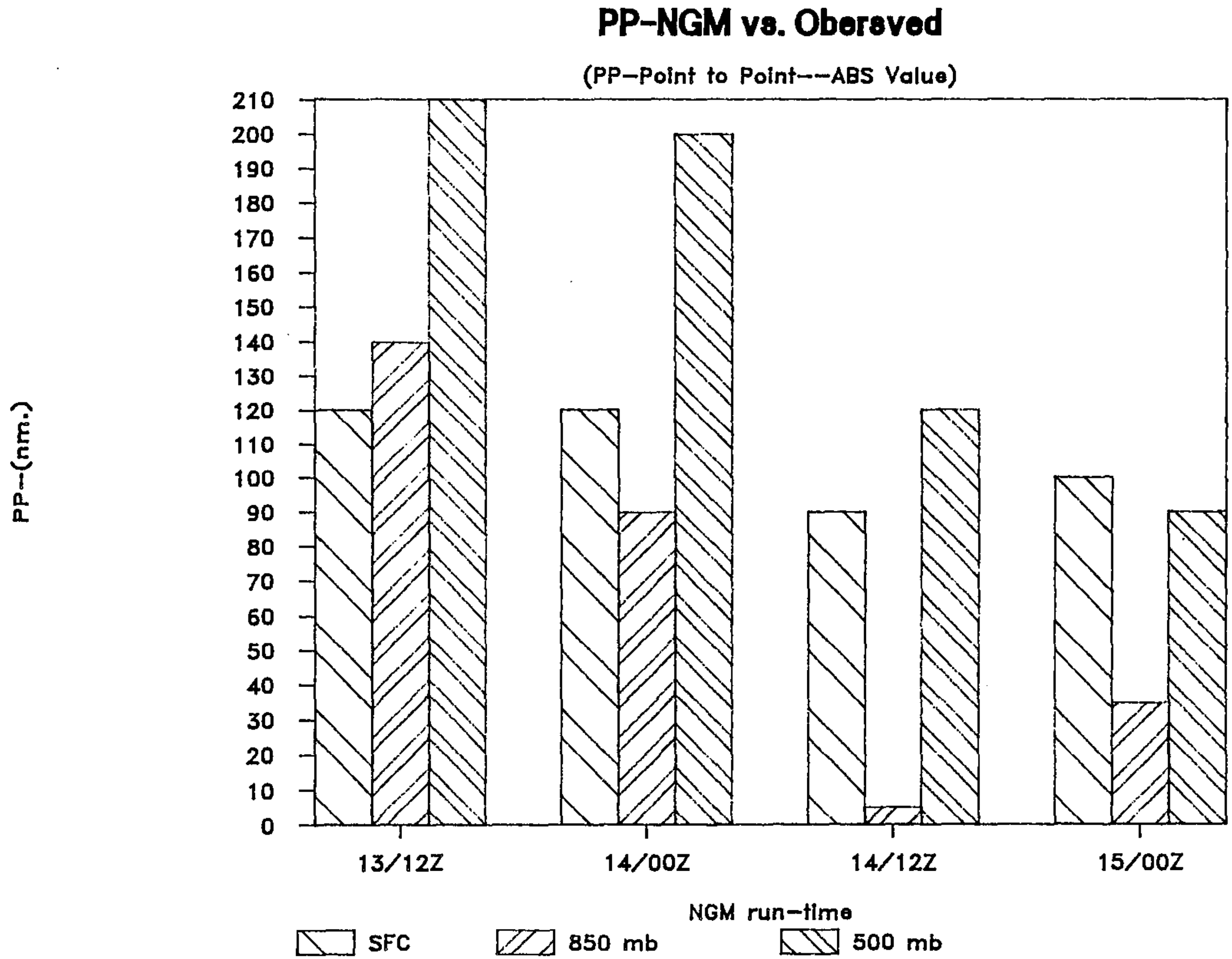

Figure 4 Comparison of NGM forecast position to observed position of low center.

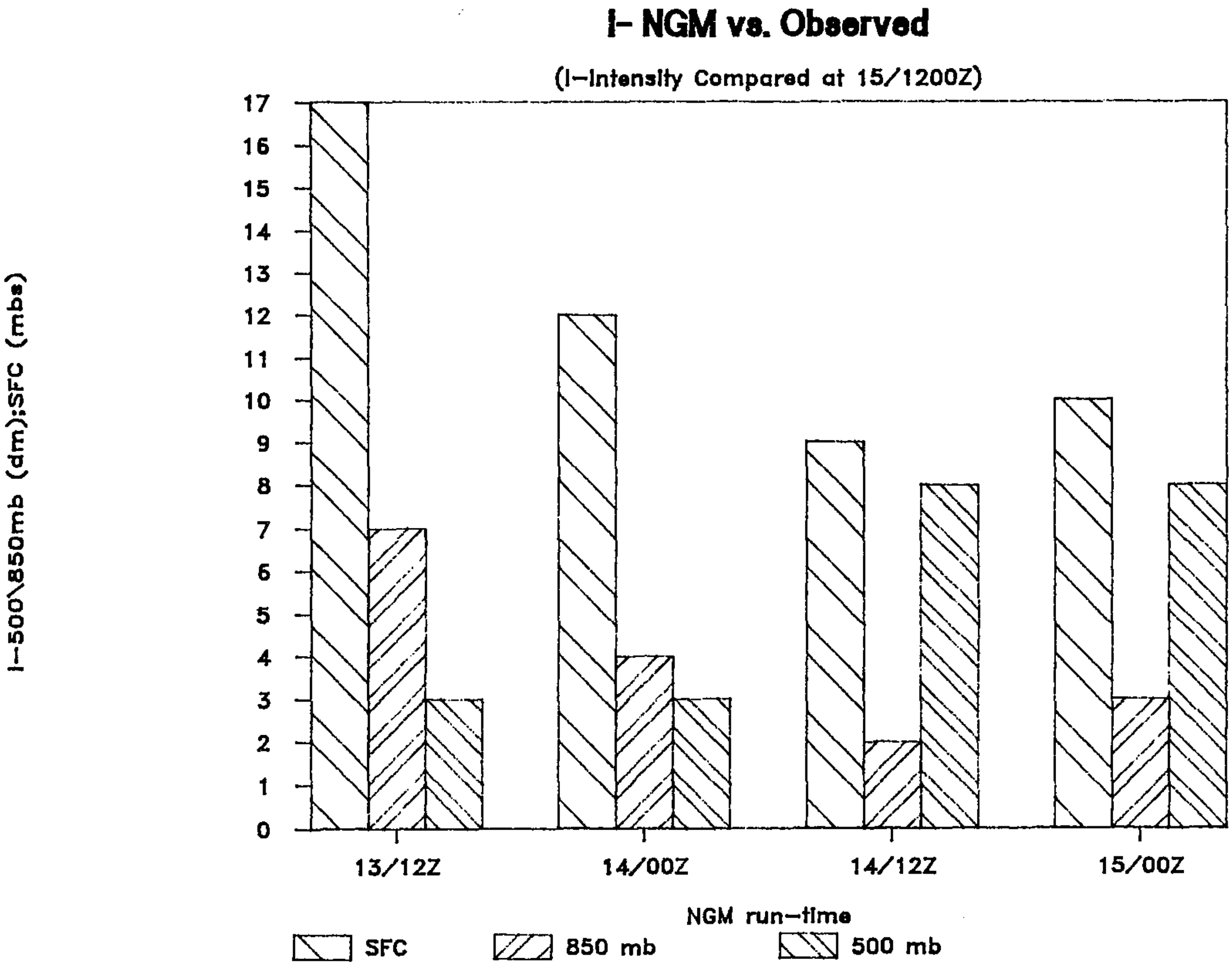

Figure 5 Comparison of intensity of NGM forecast low to observed low.

path was determined for the point at which the "closest approach" occurred (the direction of the NGM from the observed was also listed).

X "Average Distance Between Paths" (n mi) - Between NGM's prog low center's path and observed low center's path for only that portion of the low crossing Illinois (the left (+) or right (-) deviation of the NGM path from the observed path was determined by "looking" downstream along the observed path and making the comparisons). A direction comparison was also made of the paths.

PP "Point to Point" - Comparisons of the NGM's progged low center position to the observed low center position at 15/1200Z (near the time of the storm's peak intensity while over Illinois). The direction of the NGM's low center forecast position was determined in relation to the actual position.

I "Intensity" - Comparison of the NGM's low center intensity at 15/1200Z to the observed low center intensity ((+) NGM higher than actual observed, (-) NGM lower than observed).

TT8 "850 mb Temperature Field Comparison" - Comparison of NGM 850 mb forecast temperatures for 15/1200Z to observed 850 temperatures over the entire field of northern and western Illinois. Temperatures given as a range over the field ((+) NGM higher than observed, (-) NGM lower than observed).

LT "Lead Time" - Time referenced from each individual NGM initial run-time to the time of the peak intensity of the storm to affect Illinois (about 15/1200Z).

5. Concluding Remarks

The runs of the NGM model 24 to 36 hours prior to the storm affecting Illinois, all surface, 850 mb, 700 mb, and 500 mb forecasts of storm center tracks were too far to the west or northwest of the actual track and positions. In addition, the model did not deepen the storm adequately at all levels. These factors led to predicted 850 mb temperatures and 1000-500 mb thickness values that were too high and implied more rain or mixed precipitation northwest of the surface center's track than was actually observed. In fact, the storm deepened dramatically such that the precipitation over northern and western Illinois remained mostly snow. Much of the heavy snow fell in areas where convection, in the form of induced "thundersnow," occurred because of the extreme rapid deepening of the storm.

Later NGM forecasts, 12 to 24 hours prior to the storm affecting Illinois, were more closely on track with upper air and surface features (as would be expected). These forecasts, however, tracked the surface low near or to the east of the actual track - just the opposite of earlier prog runs! Forecast surface pressures, however, were still considerably too high (10 mb), while surface low speed was too slow. Temperatures and thickness values were again too high initially and this was likely a reflection of the models west or northwest position of the 500 mb low.

As a general statement the NGM model underforecast the intensity of the storm at the surface, 850 mb, and 500 mb levels. "Dynamic cooling" as the storm intensified was also underforecast. The model moved the upper level centers too far to the west and northwest. It also did the same with surface features on earlier runs. On shorter lead time forecasts, however, the NGM tracked the surface features too far east.

CENTRAL REGION APPLIED RESEARCH PAPER 97-2

PERFORMANCE OF LFM/NGM FORECAST TEMPERATURES FOR ORD - SPRING 1988

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1. Introduction

Maximum/minimum temperature guidance for O'Hare International Airport (ORD) derived from both the Nested Grid Model (NGM) and Limited-Area Fine Mesh model (LFM) was compared to actual readings from ORD for the spring (March-May) of 1988.

The deviations between predicted values by the models and observed high/low temperatures at ORD were computed, and analyzed to obtain a mean absolute error (MAE) for periods 1-4. Also, the number of times in each period that the deviation between forecast and observation was greater than 5° was calculated, as well as the number of times the difference exceeded 10°.

The MAE for a particular period was obtained by averaging the absolute values of those deviations. A mean value by month for both NGM/LFM maximum and minimum values was computed.

2. Results

One of the most prominent results of this analysis was that both models forecast temperatures that were consistently too cool for the Chicago area. In fact, upon examination of the data, where differences of greater than 5° occurred, 65 percent of the forecasted maximum temperatures were too cold, and 63 percent of the expected minima were too low (Table 1).[1]

Table 1
For Model Deviations Greater Than ± 5° % Too Cold

March	Max	79%	April	Max	59%	May	Max	58%
	Min	75%		Min	55%		Min	60%

[1] This cold bias was extreme in March (79 percent of the maximum temperatures 75 percent of the minima) but became much less pronounced in April and May. Also, both March and May were about 2° warmer than normal for the month, while April was .5° warmer.

A comparison of the 12 hour versus 48 hour forecast shows that the MAE was lowest for period 1, and higher for period 4. Not surprisingly, period 1 MAE errors were lower than the MAE's of all of the other periods (see Table 2).

Table 2
Mean Absolute Errors for PD 1 versus PD 4

PD 1	LFM	NGM	PD 4	LFM	NGM
Max	4.5	5.1	Max	5.1	5.6
Min	3.5	3.5	Min	4.6	4.1

Minimum temperature forecasts produced by the models were significantly better overall than were the forecasted maxima. The MAE for both models through the spring came out to 5.1° for highs, and 4.0° for lows, with the greater difference evidenced on the NGM data (see Table 3).

Table 3
Mean Absolute Error for Spring

	LFM	NGM
Max	4.8	5.4
Min	3.9	4.1

Forecasts of minimum temperatures improved significantly between March and May. In March the MAE for minimum temperatures was 4.9°, but by May that had dropped to a respectable 3.1° (see Tables 4, 5, and 6).

Table 4
Mean Absolute Errors for March for Deviations
PD 1-4; ORD/Models (Absolute Value)

	LFM		NGM	
	Max	Min	Max	Min
PD 1	3.7	4.4	5.9	3.7
PD 2	4.9	4.9	6.5	4.9
PD 3	5.4	4.5	5.4	4.5
PD 4	5.6	5.7	6.0	6.3

Table 5 Mean Absolute Errors for April for Deviations FD 1-4; ORD/Models (Absolute Values)				
	LFM		NGM	
	Max	Min	Max	Min
FD 1	5.6	3.1	4.9	3.4
FD 2	4.8	3.4	5.3	4.1
FD 3	5.3	3.4	5.6	4.8
FD 4	5.7	4.2	5.9	5.8

Table 6 Mean Absolute Errors for May for Deviations FD 1-4; ORD/Models (Absolute Value)				
	LFM		NGM	
	Max	Min	Max	Min
FD 1	4.1	3.0	4.4	3.3
FD 2	3.7	3.1	4.8	2.7
FD 3	4.3	2.9	5.0	2.4
FD 4	3.9	3.9	4.8	3.6

The number of extreme deviations, where forecast temperatures were greater than 10° for the observed temperature, also decreased significantly between March and May. There were approximately ten times per model in March in which the minimum temperature deviation was extreme, but only half that number in May. A similar trend was observed to occur with the maximum temperature sample. Extremes occurred 16 times per model in March, with only nine extreme cases by May (see Table 7).

Table 7 Number of Extreme Deviations (Greater Than 10°)						
	March		April		May	
	LFM	NGM	LFM	NGM	LFM	NGM
Max	14	18	13	16	7	11
Min	11	8	2	8	5	4

Summary of spring guidance performance for ORD:

March - The models were far too cold, overall, in March, and were better on minimum temperatures. The LFM was better for period 1-2 maxima.

April - The models performed nearly identically, but were again much better on minimum forecasts.

May - Similar to March performance, except not so cold. The LFM was once again better on period 1-2 maxima, and both models were better on minimum temperature forecasts versus forecast highs.

CENTRAL REGION APPLIED RESEARCH PAPER 97-3

USEFULNESS OF THE REMARK OF "BREAKS IN THE OVERCAST" TO INDICATE THAT A WINTER STORM IS OVER IN COLORADO SPRINGS, COLORADO

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1. Introduction

This study was undertaken to determine the validity of an empirical rule of thumb for ending winter storms at Colorado Springs. That rule states simply that once some form of break in the sky cover has occurred, the storm is over and that no additional significant snowfall will return.

Research into the historic background of this rule goes back to at least the early 40's when Peterson Field was established. Military forecasters used it at that time. In fact, through conversations with earlier aviation buffs that flew into Alexander Field in the 1930's such rules of thumb were in use even then. Alexander Field was located at the north end of Colorado Springs. So this particular rule of thumb is at least 50 years old.

Additionally, a review of the writings of earlier settlers or travelers that came into the Pike's Peak area in the 1800's turned up numerous accounts concerning how quickly winter storms ended in the region. Conversely they also state how quickly a storm would hit. One of the earliest recorded fierce snow storms in the region occurred April 30, 1858. A military expedition led by Captain Randolf Macy got caught in the blizzard. He lost two men in this storm. Later Captain Macy was to write "The Prairie Traveler: A Handbook for Overland Expeditions." This book was printed in 1859, and became a standard reference for westward travel. He advised, in the short chapter dedicated to this region ..."is to pass through as quickly as possible"... because of the fierce storms. Other earlier references concerning quickly ending storms can be found in books written by Howbert, Fremont, Ruxton, and Pike. So this rule of thumb could had originated with Pike's visit to the region in 1806.

In developing this study only snow storms that produced 3 or more inches of snow were considered. The criterion used was that some form of watch, warning or advisory would be in effect. Using three inches as the cutoff point kept the data manipulation from becoming overwhelming. The types of remarks that were used came from the "remarks" section of the weather observation form. Remarks such as BINOVC, THN SPOTS IOVC, SUN/MOON DMLY VSB, were the main concern, as was the ceiling becoming broken. Also considered was when the snow finally ended, and once ended did not return for 12 hours. All three inch plus snow storms since 1948 were investigated.

2. The Findings

A total of 168 cases since 1948 had 3.0 inches or more of recorded snowfall. A breakdown of the 168 cases of 3.0 inches or more snowfall is given in Table 1. Using this sample, 12Z cases had recorded in column 13 of the surface observation form the following types of remarks: BINOVC; SUN/MOON DMLY VSB; THN SPOTS INOVC ...etc. Thus, about 75 percent of the sample reported remarks.

Table 1
168 Snowfall Cases (3 Inches or Greater) Since 1948

3.0 to 5.9 inches...There were	113	cases or	67.26%
6.0 to 8.9 inches...There were	29	cases or	17.26%
9.0 to 11.9 inches...There were	7	cases or	4.17%
12.0 to 14.9 inches...There were	8	cases or	4.76%
15.0 to 17.9 inches...There were	5	cases or	2.98%
18.0 or more inches...There were	6	cases or	3.57%

Given this sample, the following interesting results were obtained:

1. Snow ended within an average of 212 minutes, or three hours and 32 minutes, after the remark was first noted.

2. Snowfall did not return within 12 hours 93 percent of the time.

3. Of those times when snowfall did occur there were six cases in which an inch or more of snowfall fell between the time BINOVC etc., was recorded and snow ended. This amounted to only 4.7 percent of the time.

4. The number of cases in which snow returned and snowfall of an inch or more occurred was 15. This amounted to 11.8 percent of the time.

Thus, after a remark (as identified above) was recorded, 88.2 percent of the time snow did not return within 12 hours nor did more than an inch of snow fall. This may be considered the WORSE CASE SCENARIO.

3. Conclusion

The rule of thumb, once some form of break in the sky cover occurs the storm is over and that no additional significant snowfall will return, proved to be very accurate, 88-95 percent of the time, depending on how one views the findings. No matter what percentage is used, it appears that once it is over it is over!

It is well known that just because the snow has ended at the Colorado Springs airport, it has not necessarily ended for the entire region. A fierce storm may still be occurring across the Palmer Divide and in the extreme eastern sections of El Paso county. It is also well know that even after a storm has ended, one may not be able to travel in any direction out of the city for a day or two. However, by terminating watches, warning and advisories in a timely manner, trustworthiness in the weather forecast may be maintained. Hopefully, this study will prove useful in reducing the time between the ending of snowfall events in which three or more inches of snow is either forecast or has occurred, and the termination of any watches, warning and advisories that may be in effect.

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CENTRAL REGION APPLIED RESEARCH PAPER 97-4

....A CASE STUDY INVOLVING THUNDERSTORM INITIATION....

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1. Introduction

Rockwood and Maddox (1988) stated that "the synoptic scale environment plays a greater role in the evolution or intensification of convective storms than it does in initiation. The initiation seems to be closely related to the mesoscale processes. For example, if the synoptic scale is unfavorable for thunderstorms, convection still may form as a result of the mesoscale processes but it is not likely to organize or intensify into a large thunderstorm system."

The following case study illustrates that without a favorable synoptic environment, only widely scattered thunderstorms developed in a very favorable mesoscale environment.

2. Case Study

At 00Z on June 18, 1988, a mesoscale environment very favorable to convection occurred in western Iowa. A surface outflow boundary, resulting from morning thunderstorms, extended from just north of Norfolk, Nebraska to between Sioux City, Iowa and Omaha, Nebraska to between Ottumwa, Iowa and Kirksville, Missouri (Fig. 1). Temperatures to the north of the outflow boundary were some 10° to 15°F cooler than to the south.

At 00Z, the Bothwell ADAP programs (1988) indicated an unstable atmosphere with LI as low as -11 centered in northeast Nebraska. There was no cap and surface warm air advection was occurring. Surface mixing ratios were high at 15 g/kg and the surface moisture flux convergence was along the surface outflow boundary (Fig. 2).

The 00Z low level thickness/mean wind chart indicated ample moisture with dew points of 12°C. The 850-500 mb thickness/stability chart indicated an unstable atmosphere with a K index of 38 and a total total of 50 (Figs. 3 and 4).

Although the mesoscale environment was favorable, the synoptic environment was unfavorable for thunderstorm development over western Iowa. At 00Z, satellite imagery indicated a weak vorticity center about 30 miles to the north of

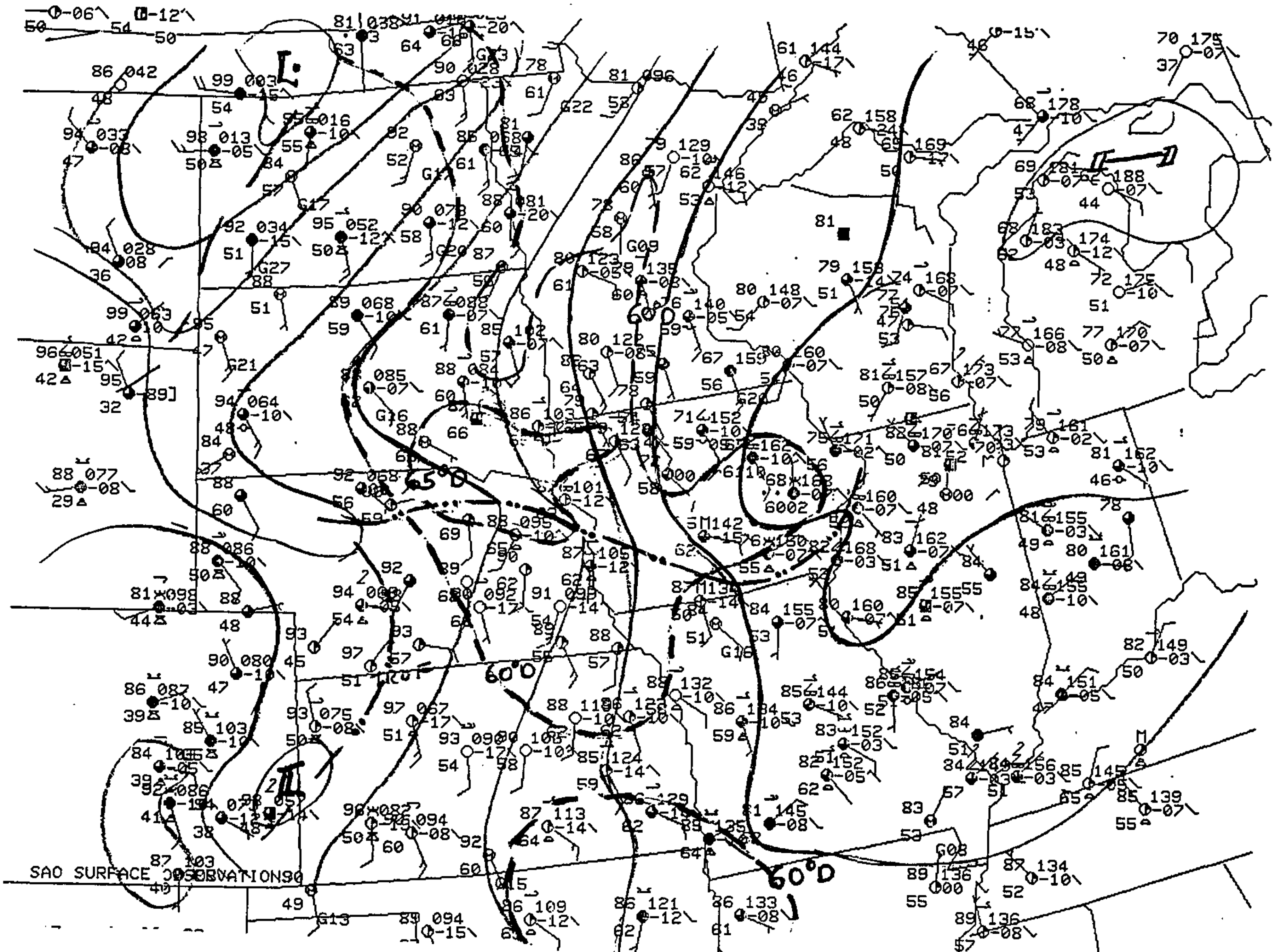

Figure 1 Surface analysis for 00Z June 18, 1988. Outflow boundary/trough line indicated by dashed dot line, dew point analysis by dashed line.

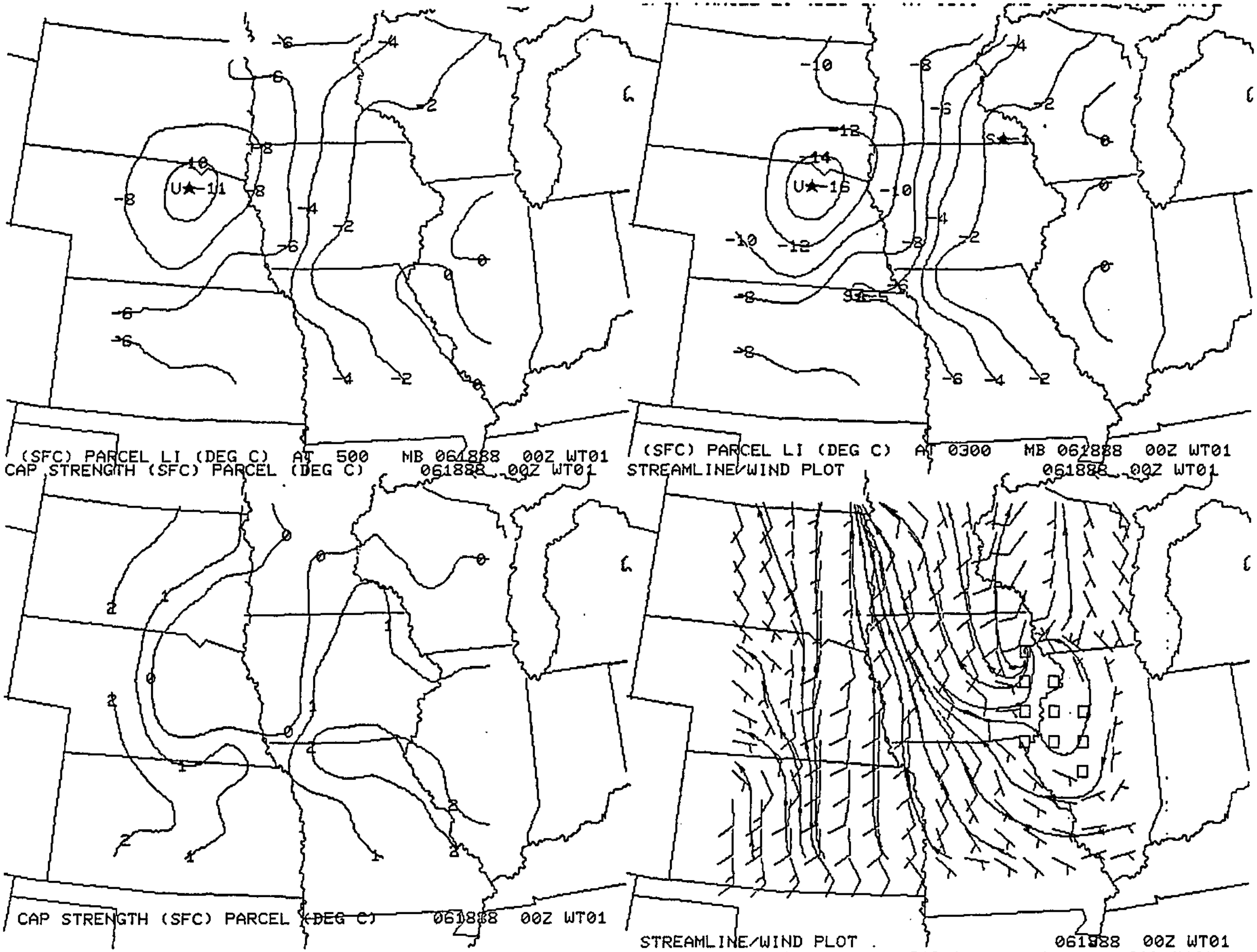

Figure 2a Mesoscale analysis data from ADAP program for 00Z June 18, 1988.

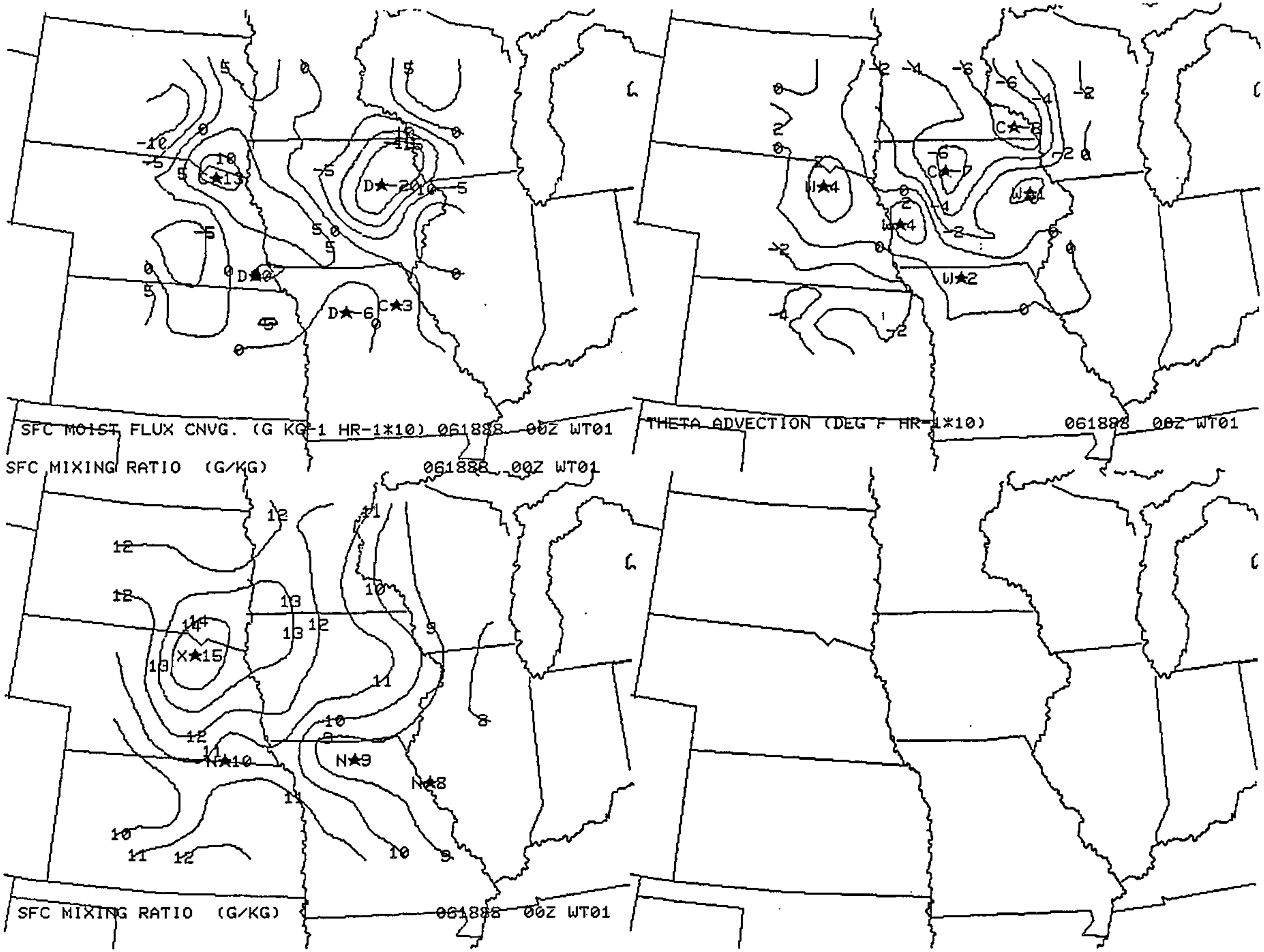

Figure 2b Same as Figure 2a.

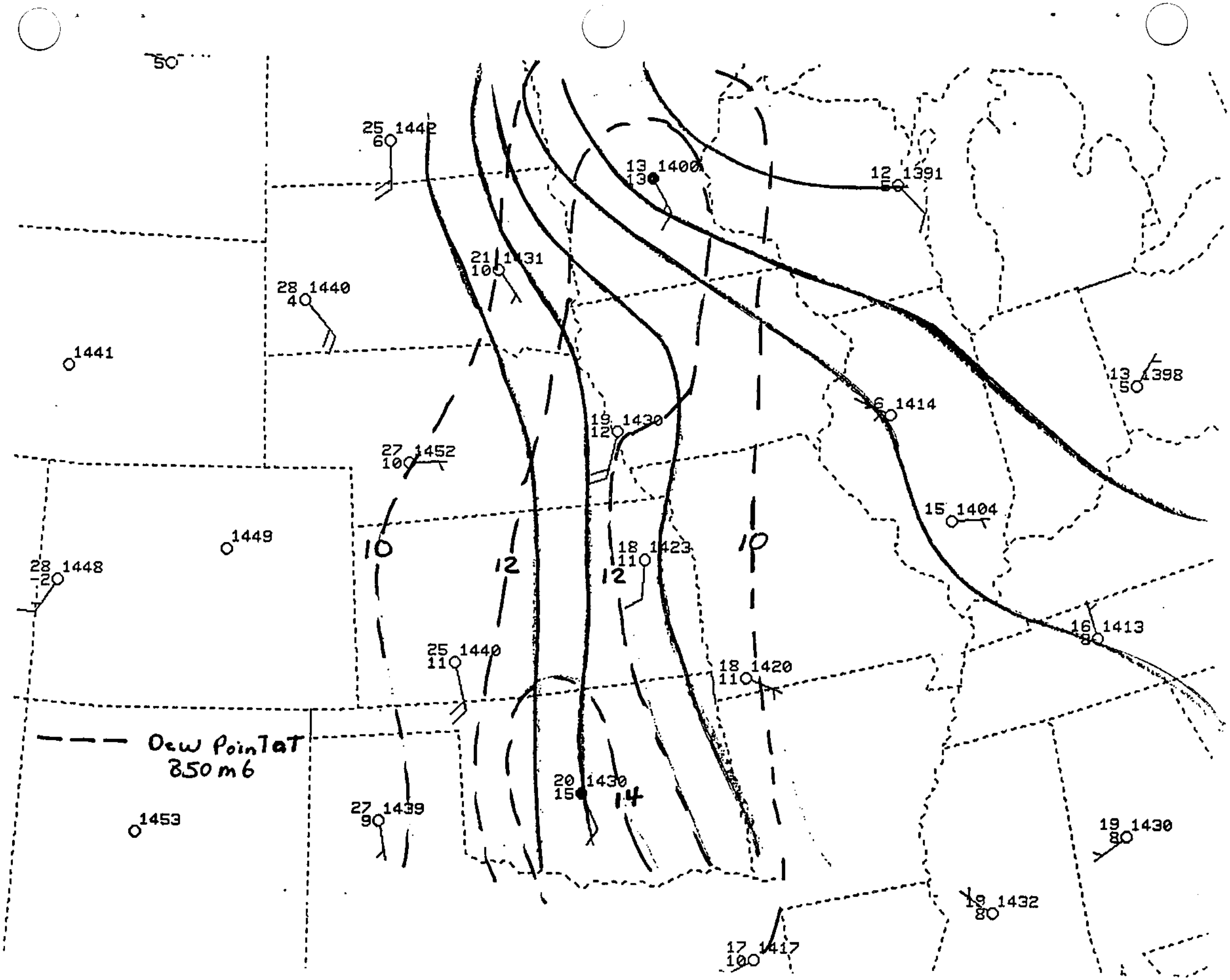

Figure 3 The low level mean wind/thickness chart for 00Z June 18, 1988; temperature °C (solid lines) and dew points °C (dashed lines).

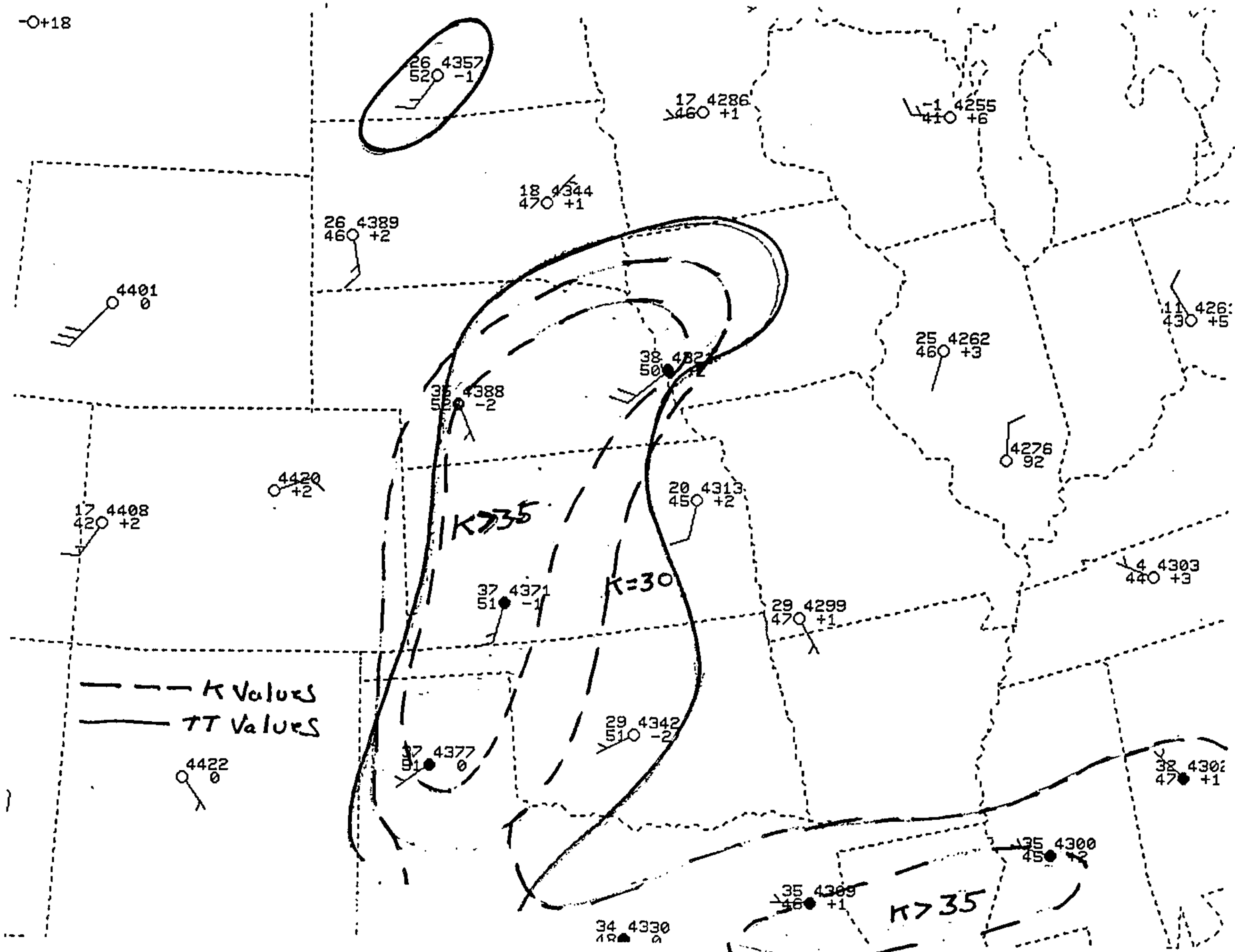

Figure 4 The 850-500 mb thickness/stability chart for 00Z June 18, 1988; Total totals (solid line) and K values (dashed lines).

Des Moines moving southeast at 25 knots. By 04Z, the vorticity maximum was located across northeast Missouri. Negative vorticity advection with subsequent sinking occurred across western central Iowa from 00Z to 06Z (Fig. 5).

At 2330Z Des Moines radar showed no echoes over western Iowa (Fig. 6a). At 0130Z one cell developed in Guthrie County in western central Iowa along the outflow boundary (Fig. 6b). At 0230Z another cell developed in Crawford County (Fig. 6c) and by 0330Z several widely scattered cells were occurring in west central Iowa and south central Iowa close to the outflow boundary (Fig. 6d). The thunderstorms then decreased in intensity as the boundary weakened and by 06Z they had dissipated (Fig. 6e).

Forecasting of this event required a knowledge of the interaction between meso and synoptic scale environments. The public forecaster issuing the forecast at 0220Z felt confident that a few thunderstorms would develop but that their extent would be limited.

3. References

Bothwell, P. D., 1988: Forecasting convection with the AFOS data analysis programs (ADAP-Version 2.0). NOAA Tech. Memo NWS SR-122, National Weather Service Southern Region, Fort Worth, TX.

Rockwood, A. L., and R. A. Maddox, 1988: Mesoscale and synoptic interactions leading to intense convection: The case of 7 June 1982. Weather and Forecasting, 3, 51-69.

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MLC. SW END OF LOBE IS PUSHING SE 25 KT. SYS APPRS TO BE GETTING
STRETCHED OUT IN LARGE SCALE DIFLUENT PAT..WITH HI CLDS SPRDG E OVR THE
LWR OH VLY AND SSE/SE ACRS THE RED RVR INTO TX. SCT CNVTN DVLPG IN SW
IA JUST UPSTRM OF THE LOBE/VORT MAX ALSO INDC WKNS OF SYS.
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Figure 5 Satellite interpolation message issued 0430Z June 18, 1988.

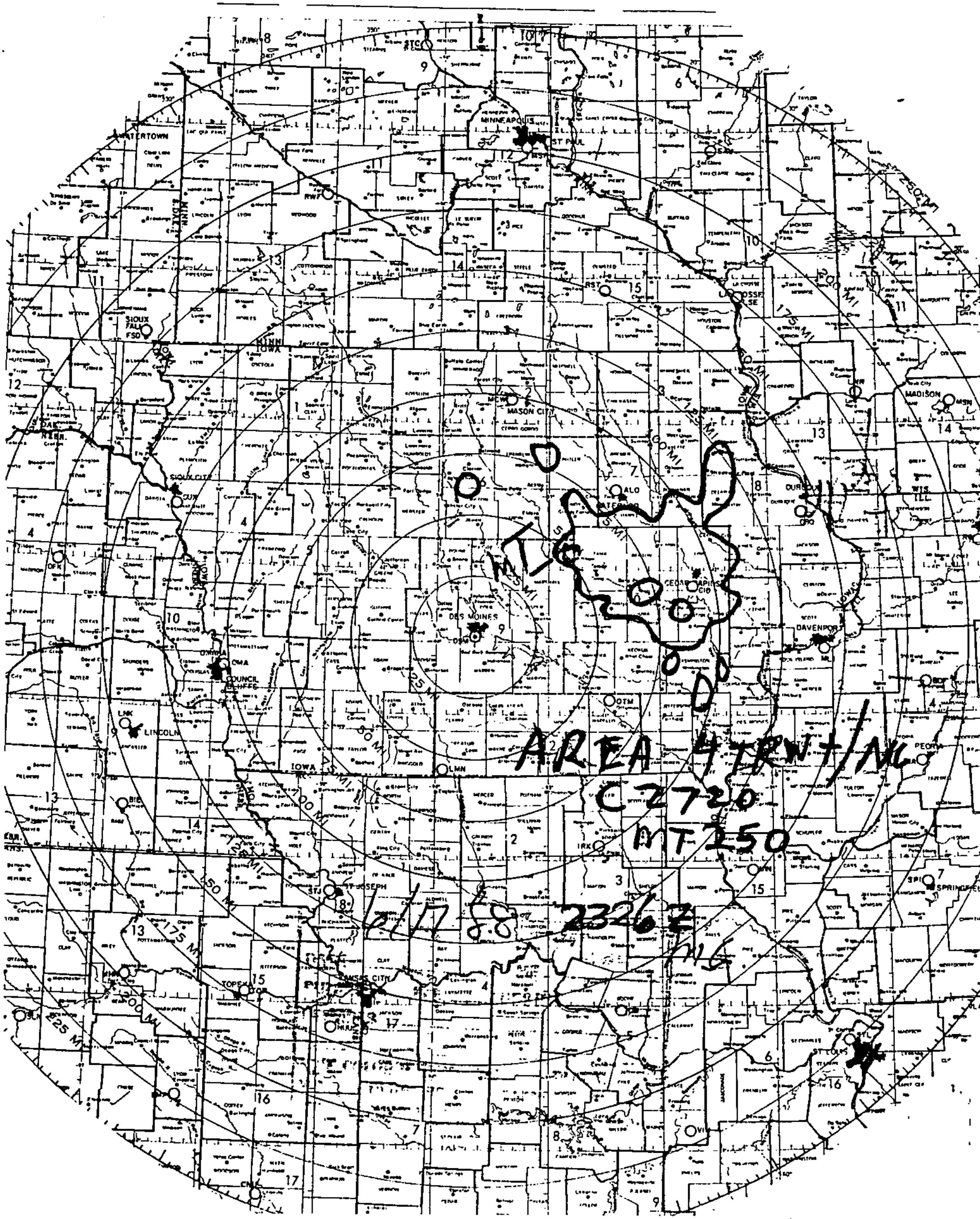

Figure 6a Des Moines radar charts for 2336Z June 17, 1988.

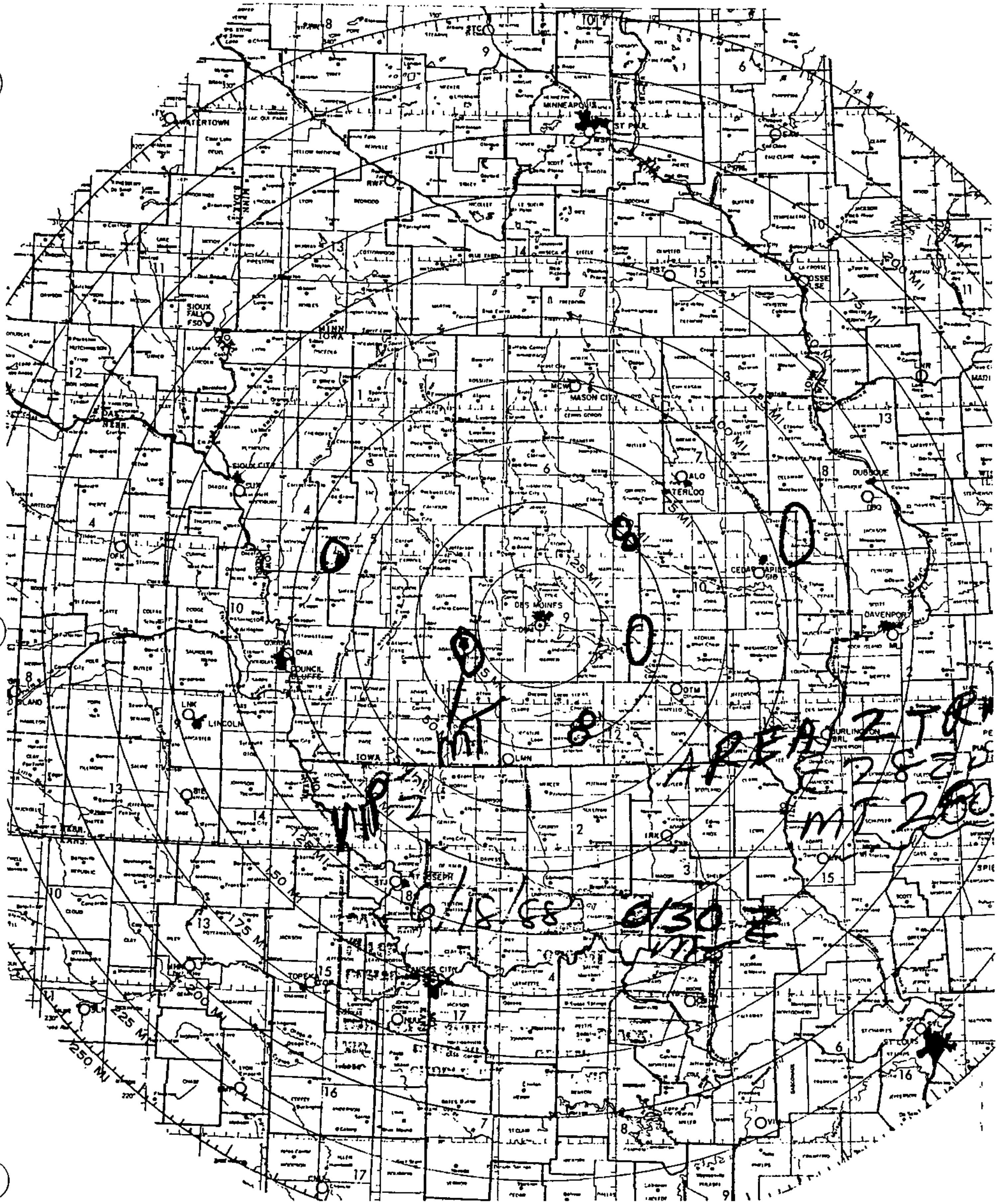

Figure 6b Des Moines radar charts for 0130Z June 18, 1988.

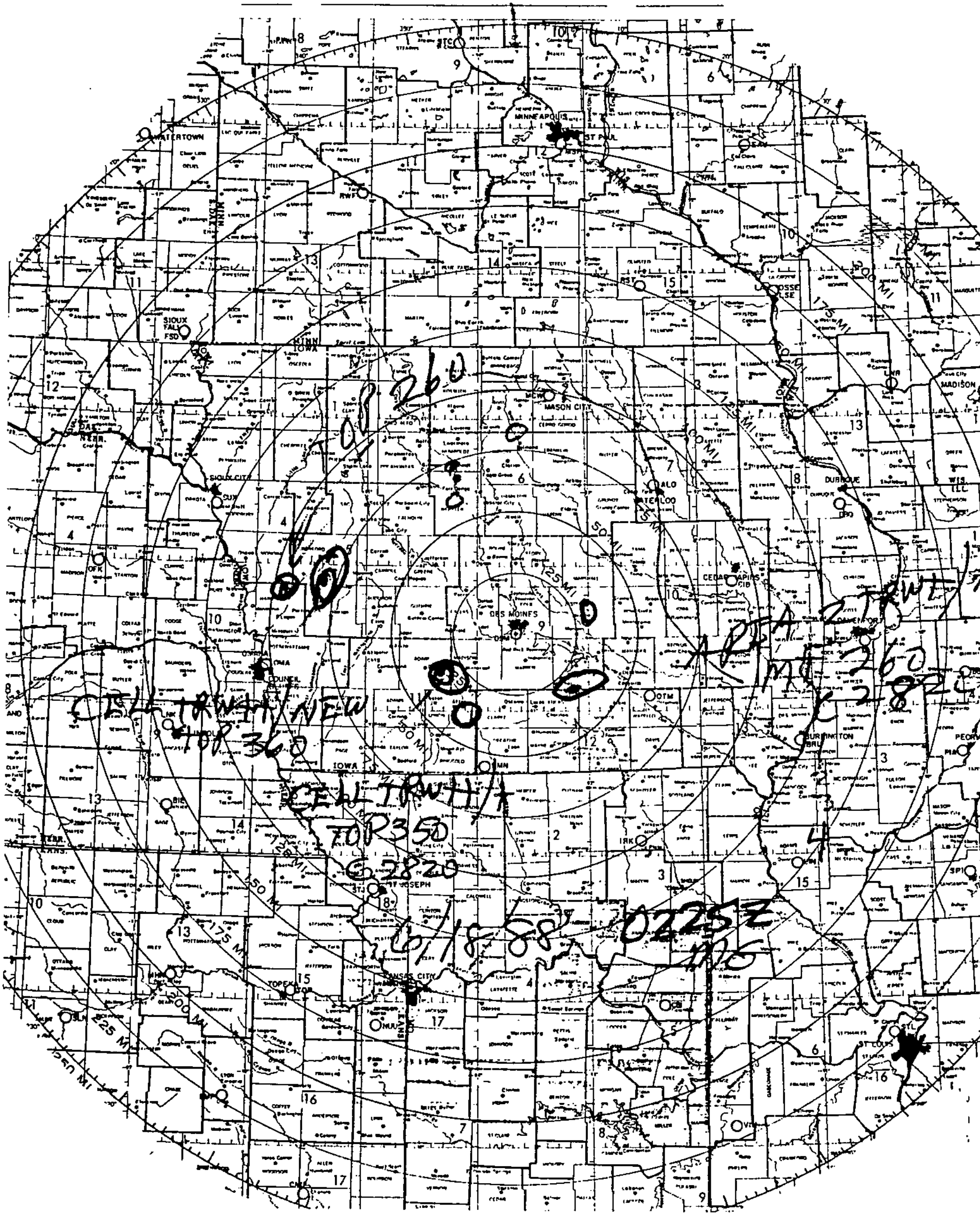

Figure 6c Des Moines radar charts for 0225Z June 18, 1988.

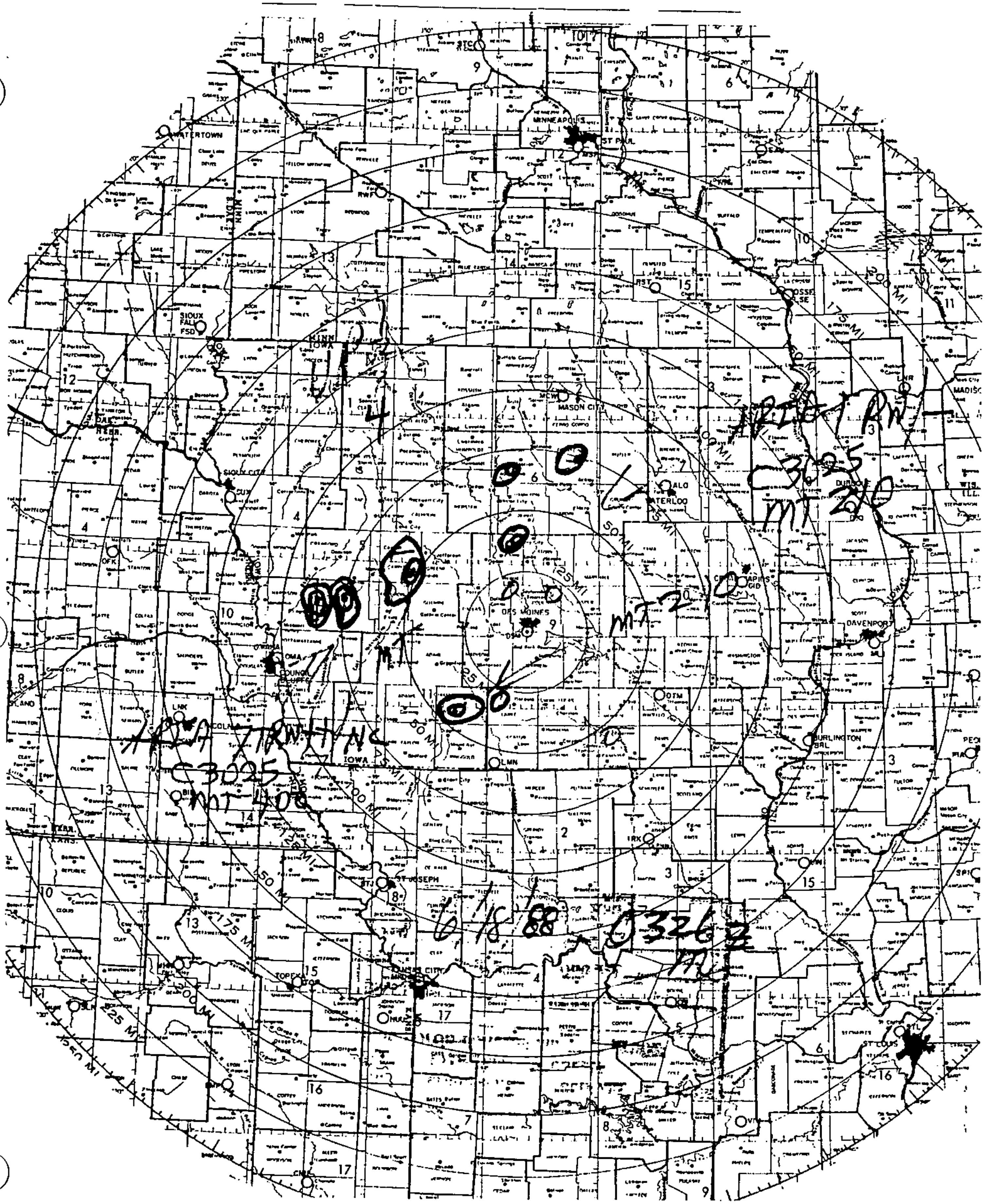

Figure 6d Des Moines radar charts for 0326Z June 18, 1988.

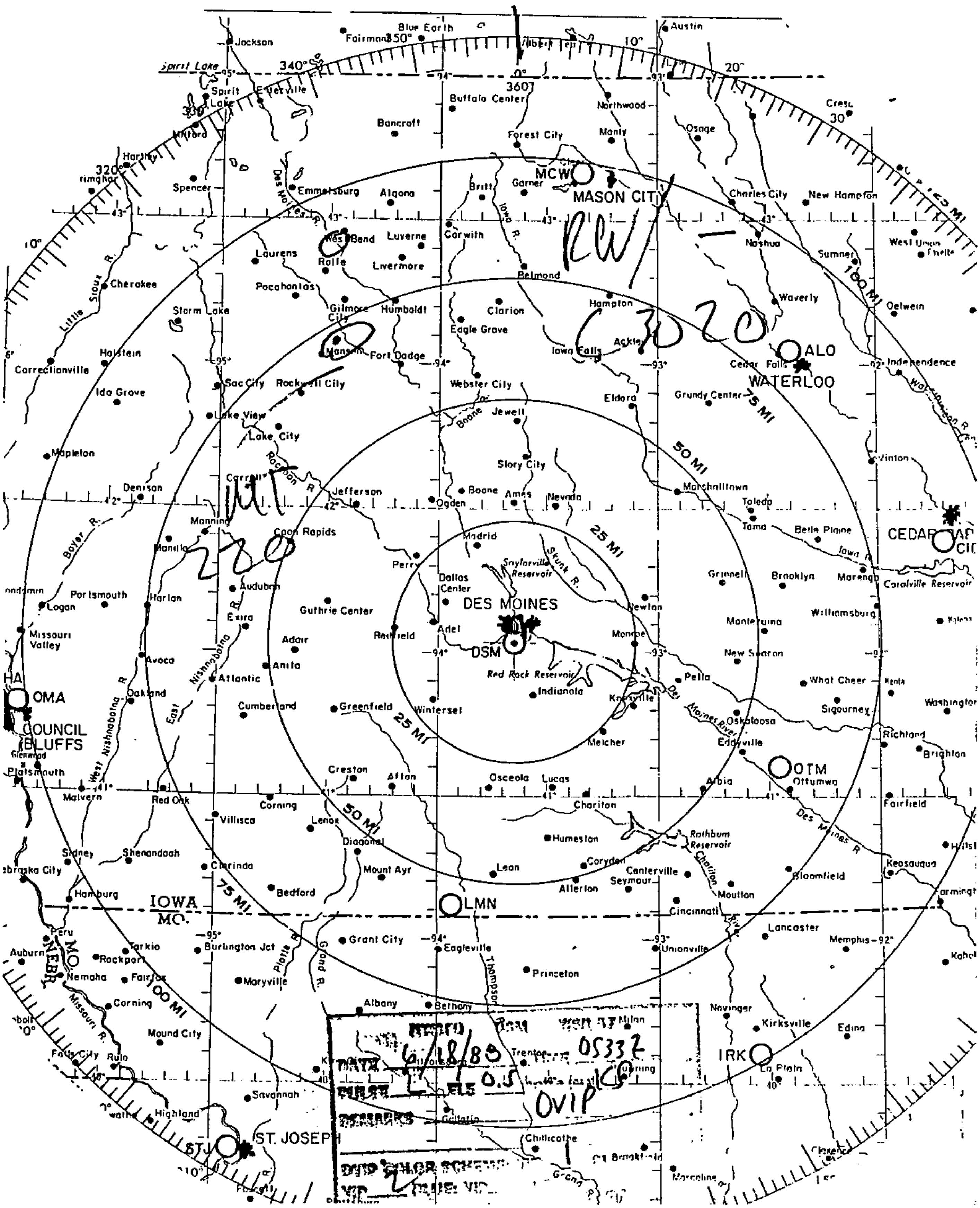

Figure 6e Des Moines radar charts for 0533Z June 18, 1988.

CENTRAL REGION APPLIED RESEARCH PAPER 97-5

"ANTIGUIDANCE" -- ARE NUMERICAL MODELS HURTING FORECASTING, OR NOT BEING UTILIZED PROPERLY?

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1. Introduction

All too often, especially during difficult forecasting situations, field forecasters encounter numerical model guidance that only complicates the forecasting process. That is, each numerical weather prediction (NWP) model that is available to forecasters has a different solution about the future state of the atmosphere -- defined here as "antiguidance" situations. This is especially critical when a public forecaster at a WSFO has to first decide what model(s) to use, and then make crucial decisions about issuing highlights such as Winter Storm Watches and Warnings, Flash Flood Watches, etc. Also included in the list is simply deciding whether or not to "beef up" particular elements of a zone forecast (or even put something in such as a 20 percent chance of thundershowers). Many times, important decisions are then made by public officials that, in turn, affect the lives of possibly millions of people. Obviously, if too many wrong decisions are made by public forecasters, NWS credibility is questioned.

With all the NWP guidance available (ERL, RGL, AVN, and MRF -- to the WSFO's), it may be that many field forecasters have become too dependent on the numerical models. That is, using the models without: (1) fully understanding their resolution and physical parameterizations, and (2), not <u>first</u> thinking about the structure of the initial state and its subsequent evolution <u>before</u> looking at the models. If this is the case, it seems that field forecasters could become "pawns" of the NMC computers.

The purpose of this study is to illustrate "antiguidance" and to give some discussion about NWP. Additionally, emphasis will be given to field forecasters using their knowledge and experience (including gaining more knowledge, especially of atmospheric dynamics). No tangible product for forecasters to use during "antiguidance" situations <u>can</u> be given here. Numerous verification studies of the models have already been published (for example, see Meteorological Operations Division Technical Note 88-1). However, those findings will not hold in <u>every</u> forecasting situation. Understanding atmospheric dynamics and the NWP models is the key to resolving "antiguidance."

In this paper, some discussion of the causes of errors in atmospheric modeling is given. Afterwards, a brief summary of the NWP models from the Technical Procedures Bulletins (TPB's) is presented. An example of "antiguidance" then follows. Additional details of the NMC models and principles of NWP can be found from the references given.

2. Discussion

a. Errors in Modeling

Errors in NWP modeling can be broken down into three causes. These are: (1) errors in detecting the initial state of the atmosphere, (2) errors involved with NWP modeling itself, and (3) atmospheric predictability.

Errors in the initial state are the result of the lack of observations (especially over data sparse regions such as the oceans and the Southern Hemisphere), and errors in the data itself. Finally, there may be objective analysis and initialization errors. Initial state errors are scale dependent. Small mesoscale features and narrow baroclinic zones may not be well resolved.

All NWP models have their limitations. There are limitations in the equations that are integrated to the future. That is, all the governing laws describing atmospheric motion are not fully known and/or terms are neglected in their mathematical development. These include horizontal and vertical resolution, truncation errors, incomplete boundary conditions, and incomplete or erroneous physics parameterizations (terrain, diabatic heating such as latent heat release, dry and moist convective adjustments, boundary layer, etc.).

Finally, there are limitations to atmospheric predictability (i.e., "chaos" is the rule). Verification studies show that initial errors grow, and double in two to three days (Holton, 1979). The smallest scales are affected first, with subsequent error growth limiting useful forecast to two to three weeks. The highest predictability is for largest scales (low zonal and meridional wave numbers). Even with perfect models, the initial state is always contaminated with error. With perfect observations, there will always be unresolvable scales of motion that eventually will cascade up to the larger scales.

b. Summary of NWP Models Available to Field Forecasters

The NMC NWP models available to WSFO's are the NGM, RGL, AVN, MRF, LFM ERL. The details of each of these models from the TPB's are summarized below. Considerably more detail can be found from the TPB's listed in the bibliography (as well as those not listed).

The Nested Grid Model (NGM) is the forecast model of NMC's Regional Analysis and Forecast System (RAFS). RAFS consists of three computational components: (1) the Regional Optimum Interpolation analysis (ROI), (2) the Nonlinear Normal Mode Initialization (NNMI) step, and (3) the Nested Grid Model (NGM) prediction component.

The NGM is a 16-layer vertical resolution (sigma coordinates), hemispheric, grid point primitive-equation model. It is run operationally in a three-grid (staggered grid) configuration with its greatest horizontal resolution over North America. Resolution of its innermost grid (over North America) is 91.5 km at 60° North latitude (polar stereographic map projection).

The NGM analysis incorporates significant level data. Its analysis variables are height, wind, and specific humidity. Also, the regional analysis uses satellite temperature observations to construct height corrections to the first guess, and makes wind corrections assuming that the wind and height are geostrophically related (the LFM does not do the above). The analysis of the NGM uses three dimensional, multivariate optimal interpolation.

Non-linear normal mode initialization provides the initial fields for the NGM forecast (initialization comes after the analysis step). This initialization consists of setting the amplitude and time tendency of high frequency gravity waves to zero. Much of the details of the physics of the NGM can be found in TPB Series No. 363.

The Aviation model (AVN) is simply the NMC's Global Spectral Model run to 72 hours. It has a horizontal resolution of 80 triangular truncation waves (T80). The model has 18 vertical layers. The T80 truncation works out to an effective grid size of about 150 km in mid-latitudes (remember that this is NOT A FINITE-DIFFERENCE MODEL! -- THE FORECASTS ARE DONE IN WAVE SPACE). The AVN uses a version of optimum interpolation for analysis and NNMI for initialization.

The Medium Range Forecast (MRF) uses the same model as that of the AVN, but it is integrated out to ten days. It runs only at 00Z since it takes so much computer time (see TPB's for details). The model provides guidance for medium range outlooks.

The LFM (Limited-area Fine Mesh) has the earliest data cut-off time, and the lowest horizontal and vertical resolutions of the models. Its analysis, initialization, and forecasts are for a relatively small area (centered on North America). It is the first NWP output to the field. Hence, the term "early" (ERL) that field forecasters are familiar with. The model has seven vertical layers (the first three layers typically extend from the surface to above 500 mb) with a horizontal resolution of 190.5 km at 60° North latitude. The analysis considers only mandatory level data and uses the distance dependent Cressman successive corrective method. The LFM's initialization consists of simply removing the divergent (irrotational) part of the analyzed wind field. Please see the listed TPB's for details of the model's physics.

c. Example of "Antiguidance"

The intention of the above discussion was to serve both as background information and as stimulation to forecasters to do further investigation of NWP and the operational guidance available. A case of "antiguidance" is now discussed. It occurred on Sunday, May 1, 1988.

The numerical model output based on 12Z Sunday data is shown. To show other "model runs" would require too much length given the purpose of this paper. Also, not all the fields of output ("all panels") can be shown. Only a few selected panels to illustrate the main points are presented.

On Sunday, May 1, 1988, during the day shift at WSFO Cheyenne, a winter storm watch for the southeastern half of Wyoming was issued to go into effect for the following Monday and Monday night. Advisories were posted for the rest of the state. Other WSFO's over the Northern Rockies and Northern Plains were in at least general agreement with the thinking of WSFO Cheyenne.

Figure 1 is the 500 mb analysis for 12Z Sunday, May 1. There is a trough in the height field at about 114°West longitude with a long wave ridge downstream from Wyoming over the central U.S. The lowest 500 mb heights are just east of Ely, Nevada. Note that the magnitude of the velocity field is a bit stronger west of the trough than to its east. [At 300 mb for this time (not shown), there were two wind speed maxima (of about equal magnitude), one east and one west of the trough.] Also, observe on Fig. 1 the height falls southeast of the lowest 500 mb heights. Additionally, the trough in the temperature field is west of the trough in the height field. Thus, quasi-geostrophic theory (Holton, 1979) suggests that the trough is still "digging." The eastern 300 mb wind maximum may be indicative of a separate upper tropospheric short wave rotating northeastward around the "digging" geopotential trough (that did turn out to be the case). Because of the strong evidence from the analyses of cyclonic vorticity advection and differential cold advection into the trough, one would expect that a closed cyclonic circulation would evolve and move slowly eastward. With that being the case, Wyoming would not get a severe snowstorm. While proving the above argument requires computations, a meteorologist should qualitatively see this instantly.

But what did the available numerical guidance from NMC show? Figure 2 is a plot of the forecasted positions of the "500 mb low" and its associated maximum in absolute vorticity (or "vort max"). The solid line is the NGM, dashed the AVN, and the dots are for the LFM. From Fig. 2 we see that the NGM is the farthest north, with the LFM showing the most southerly track with respect to Wyoming. The forecasts for the other fields (such as the positions of the surface low, 700 mb height and vertical motion, relative humidity, QPF, etc.) all followed suit with the 500 mb forecasts.

Figure 3 is the 36 hour NGM 700 mb height and vertical velocity forecast valid 00Z Tuesday, May 3, 1988. Note the closed low over eastern Colorado and +15 microbars (10E-06 bars; what is actually shown is negative vertical velocity in pressure coordinates, or "negative omega") per second upward vertical motion along the eastern border of Wyoming. The model also predicted greater than 90 percent mean relative humidity for all of Wyoming except the extreme west for this time. For the whole 48 hour integration starting 12Z Sunday, May 1, 1988, the model predicted more than two inches of liquid precipitation at CYS (which would have been more than 20 inches of snow since it was cold enough). Figure 4 is the same forecast product from the AVN model. It shows the same features as Fig. 3, but a little farther south and east. As can be seen from recalling Fig.

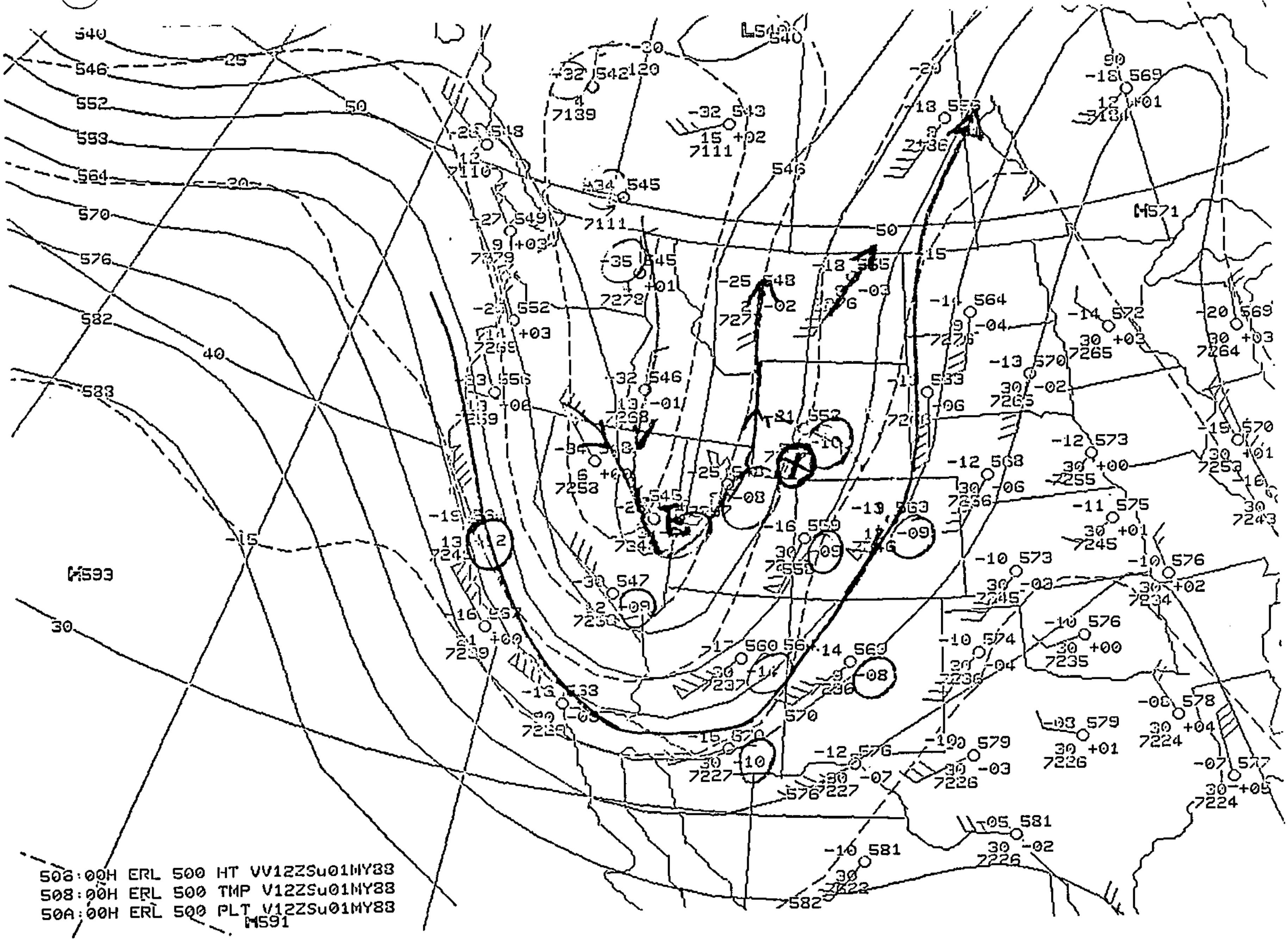
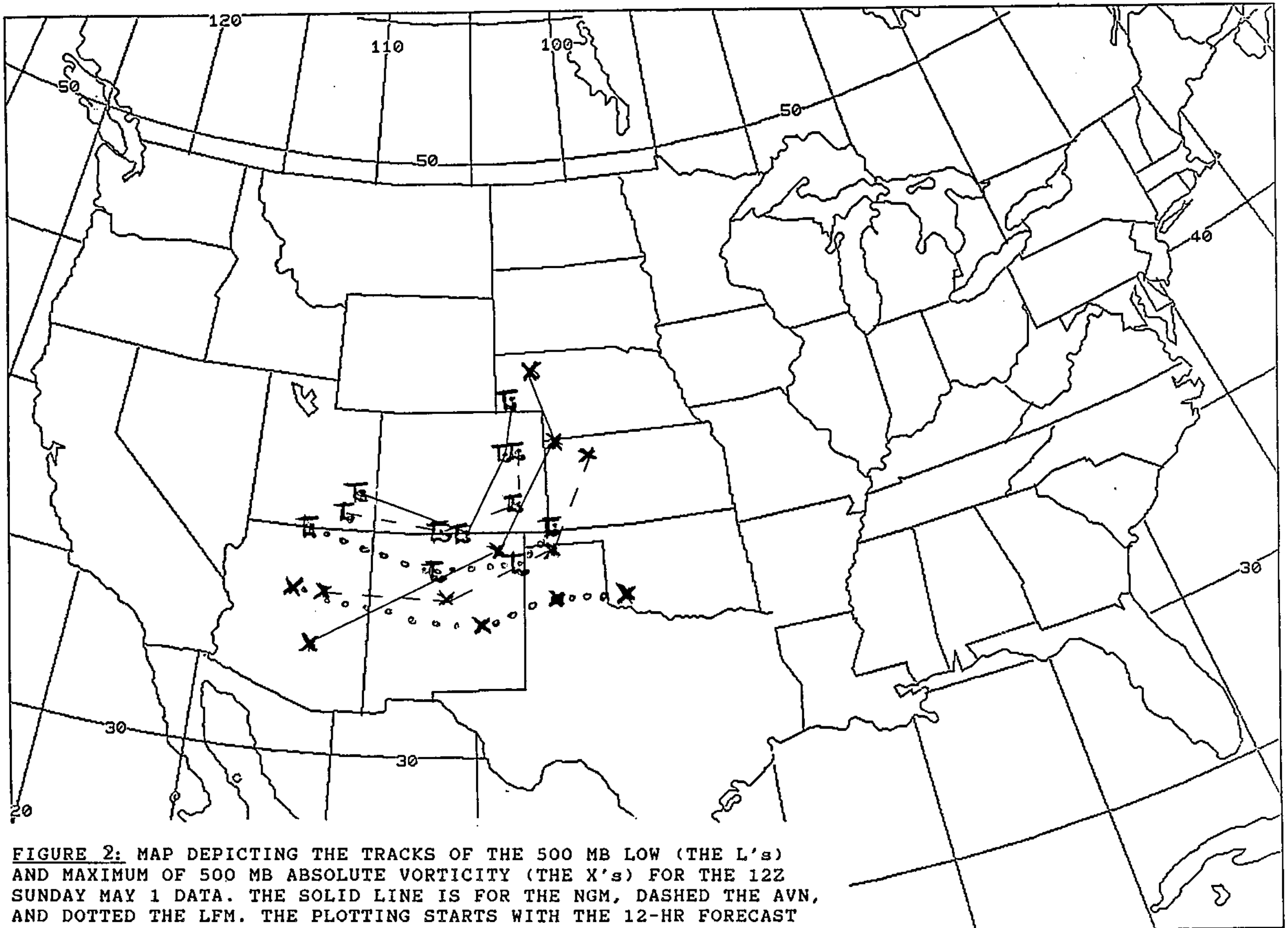


FIGURE 1: 500 MB ANALYSIS VALID 12Z SUNDAY MAY 1 1988. SOLID LINES ARE THE HEIGHT CONTOURS, DASHED THE ISOTHERMS. STATION PLOTS AND ALL UNITS ARE CONVENTIONAL. ARROWS ARE STREAMLINES. IGNOR OTHER LINES.



<u>FIGURE 2:</u> MAP DEPICTING THE TRACKS OF THE 500 MB LOW (THE L's) AND MAXIMUM OF 500 MB ABSOLUTE VORTICITY (THE X's) FOR THE 12Z SUNDAY MAY 1 DATA. THE SOLID LINE IS FOR THE NGM, DASHED THE AVN, AND DOTTED THE LFM. THE PLOTTING STARTS WITH THE 12-HR FORECAST VALID 00Z MONDAY MAY 2, 1988. EACH PLOTTED POSITION ARE FOR THE INCREMENTAL 12-HR FORECASTS, WITH THE TIME FOR THE LATEST PLOT BEING 12Z TUESDAY, MAY 3, 1988. FOR THIS FIGURE, THE TIME FOR THE PLOTS PROCEEDS GENERALLY FROM LEFT TO RIGHT.

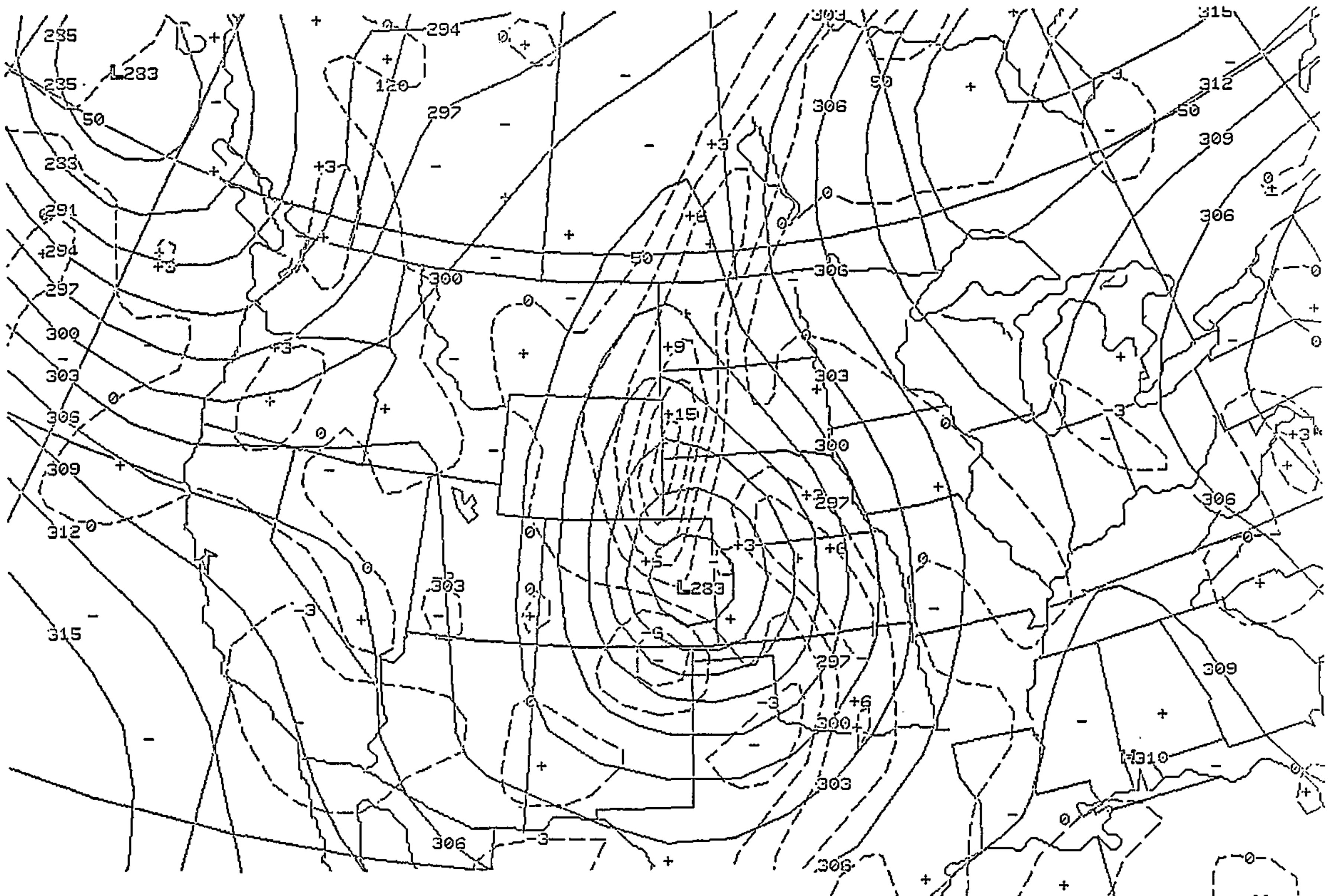


FIGURE 3: MAP DEPICTING NGM 36-HOUR FORECAST OF 700 MB HEIGHT (SOLID) AND VERTICAL VELOCITY (DASHED). THE VALID TIME IS 00Z TUESDAY, MAY 3, 1988. UNITS OF VERTICAL VELOCITY ARE 10E-06 BARS PER SECOND (MICROBARS PER SECOND) AND INCREMENTS ARE SHOWN FOR EVERY 3 MICROBARS PER SECOND. 700 MB HEIGHT IS CONVENTIONAL.

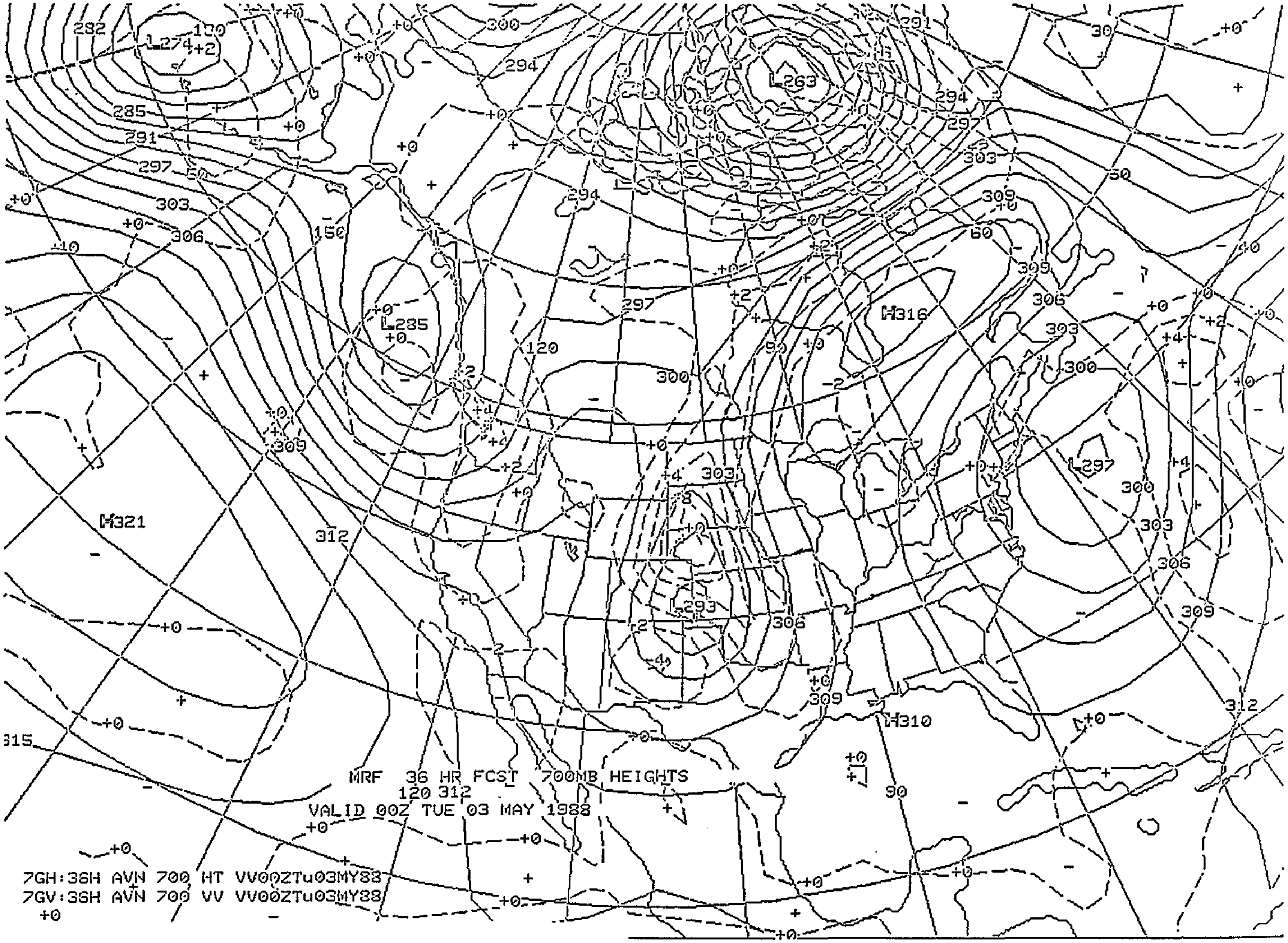


FIGURE 4: SAME AS FIGURE 3 BUT FOR AVN.

2, the AVE was a compromise between the NGM and LFM (this was true for all model output.)

Figure 5 shows the 48 hour NGM forecast of sea level surface pressure and 1000-500 mb thickness valid 12Z Tuesday, May 3, 1988. Note the surface low over extreme northern Kansas. The model was moving the lowest surface pressure slowly northeastward from eastern Colorado starting 12Z Monday to the position shown in Fig. 5. Also, observe the magnitude of the pressure gradient across eastern Wyoming. If this model were to verify, blizzard conditions would occur by Tuesday morning. The corresponding 48 hour AVN (not shown) was essentially identical to Fig. 5 and it also tended to move the surface low northeastward. Figure 6 is the same as Fig. 5 except for the LFM. Note that while the LFM sees a weak low over central Colorado, the principal surface low is over extreme northeastern Texas. Also, the model was moving the surface low east-southeastward from 12Z Monday to 12Z Tuesday. The LFM was in sharp disagreement with the other two models. If the LFM scenario were to verify, Wyoming would receive some snow, but not a winter storm as defined by NWS criteria. For completeness, the MRF was "not used" since it is available only with 00Z runs and not all of it's output is available on AFOS to WSFO Cheyenne. However, it's 500 mb forecasts were in agreement with the AVN and NGM.

As stated earlier, a winter storm watch was posted for about the southeastern half of Wyoming on Sunday, May 1 to go into effect for Monday and Monday night. The Sunday evening shift updated the watch to a warning. That was because the NGM run based on 00Z Monday data was essentially identical in all aspects to the 12Z Sunday run. The overnight AVN run was also "the same" as the 12Z Sunday run. The 00Z Monday LFM continued to be different in moving the low and all fields eastward, not essentially straight north like the other two models. The midnight shift continued the warning. Until the model runs based on 12Z Monday data were available, at least four sets of model output (starting with the 12Z Saturday runs) from the AVN, NGM, and LFM were the same in their forecasts like that shown for 12Z Sunday output. Forecasters went with the NGM and AVN, and "threw out" the LFM.

So what happened? The LFM was the winner and the warnings were a big bust!! Referring back to the previous discussions, there was an upper tropospheric maximum in cyclonic relative vorticity rotating around the "digging" trough. The first effect of this was to generate an area of snow that did move northward across eastern Wyoming on the morning of May 2. With there being near blizzard conditions in Cheyenne during the morning rush hour (before 8:00 a.m.), and since there was a winter storm warning in effect, public officials called off school. Serious consideration was also given to closing state and local offices. However, since the main system moved straight eastward from Colorado (the low was "vertically stacked" starting around 12Z Monday) to eventually the Ohio Valley, the snow ended during the morning. Major forecast revisions were needed. About two inches fell at WSFO Cheyenne, not 20 inches!!

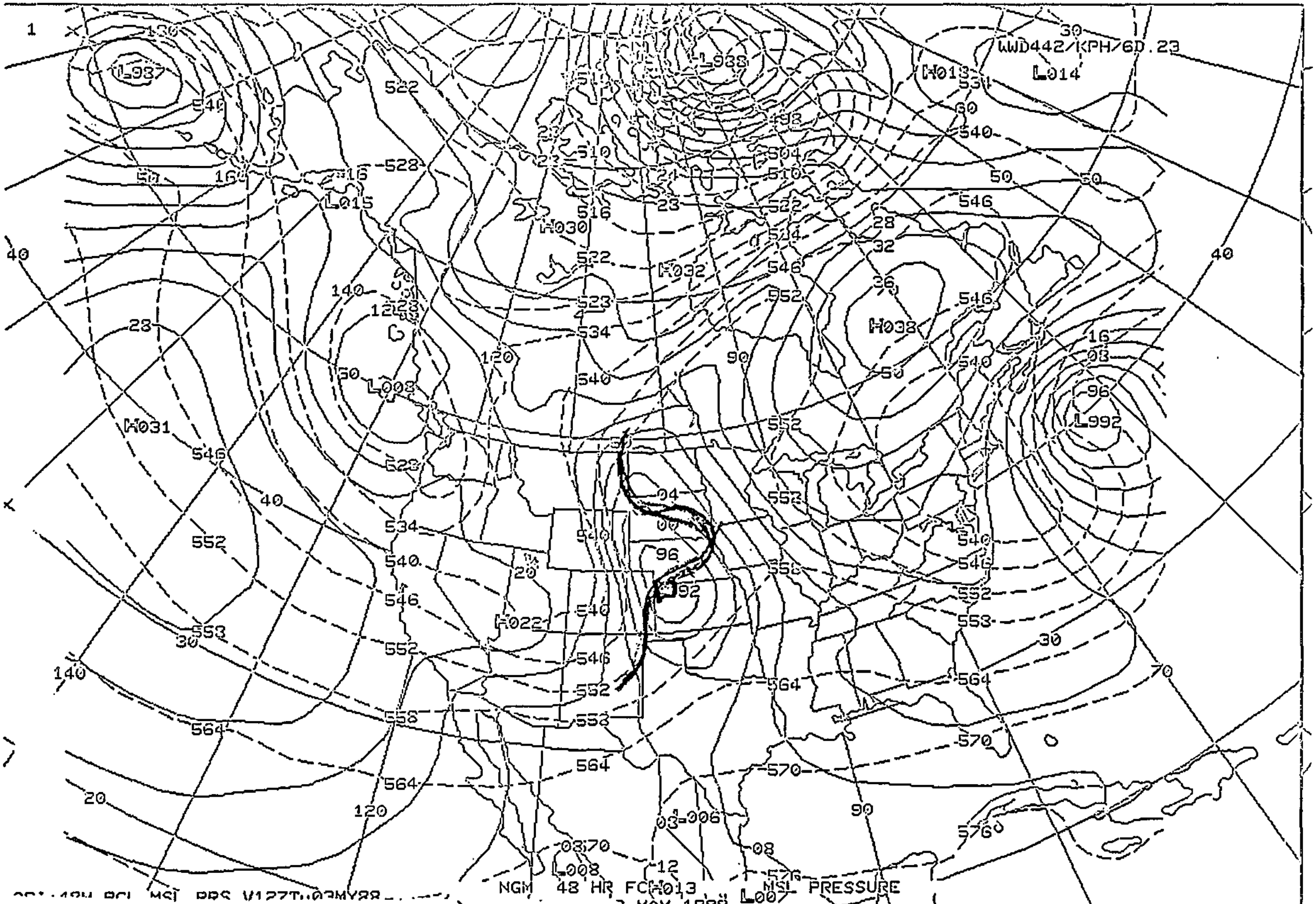


FIGURE 5: NGM 48-HR FORECAST OF SURFACE SEA-LEVEL PRESSURE (SOLID) AND 1000 TO 500 MB THICKNESS (DASHED) VALID 12Z TUESDAY, MAY 3, 1988. UNITS AND CONTOUR INTERVALS ARE CONVENTIONAL. IGNOR HEAVY SOLID LINE.

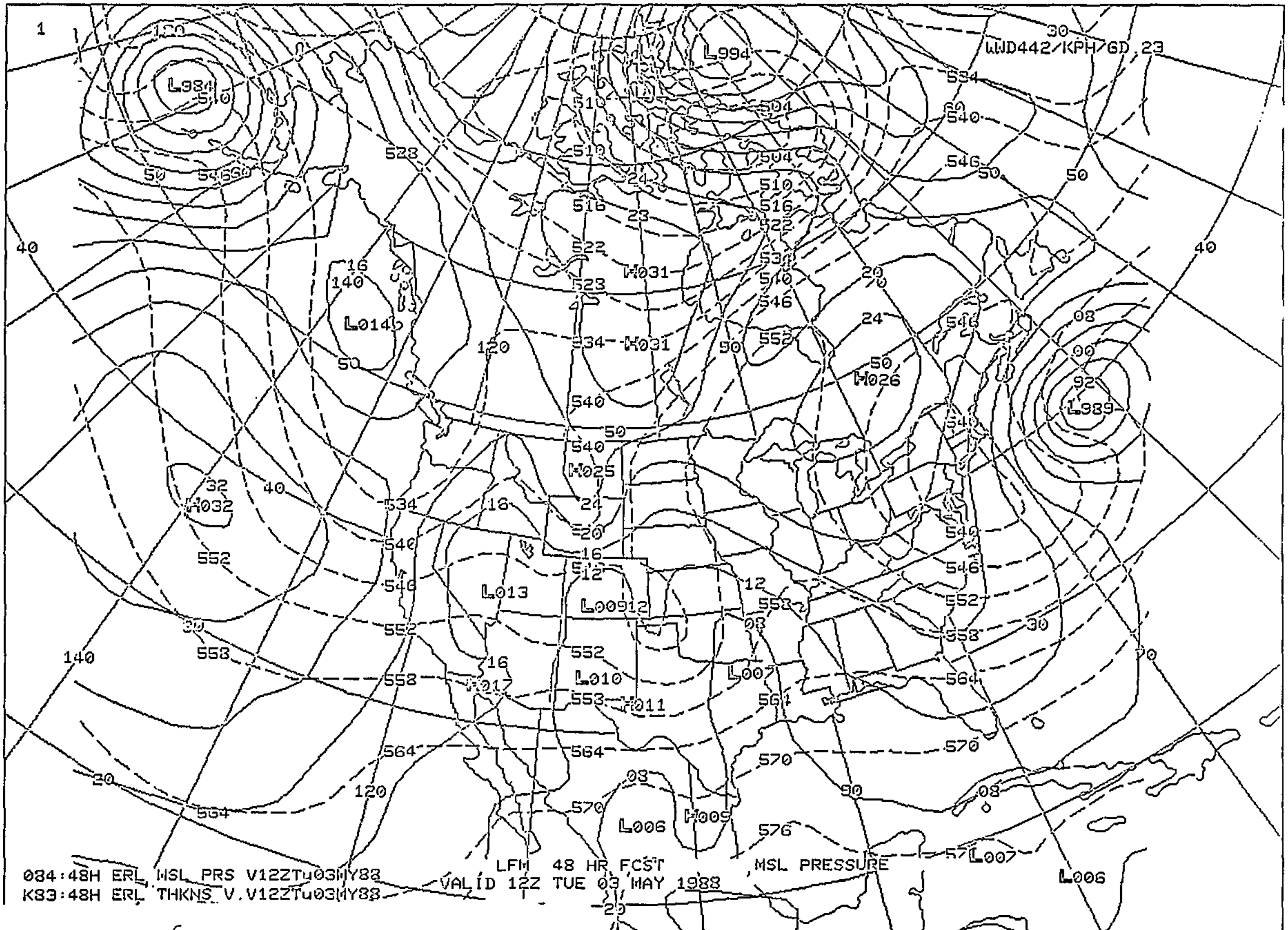


FIGURE 6: SAME AS FIGURE 5 BUT FOR LFM.

The model runs based on 12Z Monday data all were in agreement with moving the low at all levels eastward. This is what the LFM showed 24 hours ago. An effect of the "upper level vort max" discussed above might have been to cause both the AVN and NGM to produce such large forecast errors. With their elaborate parameterizations of physics, high resolution (especially the NGM), and sophisticated initialization procedures the NGM and AVN models overdeveloped the first northeastward moving "upper level vort max." It is well beyond the scope of this paper to prove this. However, the reader is strongly urged to review the referenced TPB's and to study textbooks about NWP and dynamics to help in finding answers to what the author believes is becoming a major problem for forecasters -- "antiguidance" (an excellent textbook by Haltiner and Williams is given in the reference list).

For this particular case, there was evidence that the trough in the middle and upper troposphere was still "digging" at 12Z Sunday, May 1. Yet, the NGM and AVN were suggesting the storm would move essentially straight north after 12Z Monday, May 2. This solution seemed reasonable to most forecasters because of the presence of a large amplitude downstream ridge over the central U.S. and strong "upstream kicker." [As seen in Fig. 3, the AVN showed a closed low with a trough in the 700 mb height field northwest to southeast oriented approaching the Pacific Northwest - this storm did deepen down the West Coast a few days later]. Thus to many forecasters, with such a strong storm upstream and "big ridge" downstream, the developing closed low at all levels had "no where to go" but north after 12Z Monday (even the NMC heavy snow discussion was predicting snow to be measured in feet over southeastern Wyoming by Tuesday morning, May 3).

More thought (and maybe respect) should have been given to both what the initial state of the atmosphere and LFM were "trying to say" that Sunday morning. Most forecasters felt the downstream ridge was a "block." This kind of terminology can be very misleading. Nothing in the atmosphere behaves like a block of wood. The atmosphere is a fluid governed by physical laws that are constantly ongoing. It makes absolutely no sense to say that the downstream ridge would stop this Rocky Mountain storm from moving east.

3. Conclusions

Too often, field forecasters encounter situations where output from each of the operational NMC numerical models has it's own solution about the future state of the atmosphere. Many times, these solutions can be radically different from each other. These cases where different numerical models have different solutions is what has been defined as "antiguidance." If forecasters become too dependent on the models, then these "antiguidance" situations can hurt operational forecasting and NWS credibility.

No tangible product can be given to forecasters that would solve this problem. The key is remembering that models are only guidance -- the final forecast decision must come from an understanding of the dynamics of the atmosphere and knowledge of the resolution and physics of the various NMC NWP models. Results of previous NWP verification studies, although helpful, will not work every time. Forecasters must constantly review and understand atmospheric dynamics and NWP to more easily cope with difficult forecasting situations.

Finally, other forms of guidance to forecasters are also available. These include MOS (model output statistics) analog studies and decision trees. The latter is especially true for situations involving whether or not severe convection will develop. These are fine as long as it is remembered that these are only forecasting aids and will not work every time, especially during "antiguidance." The screaming message to forecasters is to think and learn more about atmospheric dynamics and NWP for all time and space scales.

4. Acknowledgements

The author wishes to thank Mr. William T. Parker for the term "antiguidance" and helpful discussions. Also, most of the errors in modeling portion of the paper was taken from a class lecture given by Dr. Frederick Carr, Meteorology professor at the University of Oklahoma, Norman, Oklahoma, several years ago.

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CENTRAL REGION APPLIED RESEARCH PAPER 97-6

A BEDEVILING EXPERIENCE

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1. Introduction

It was a leisurely afternoon in the forecast office in Louisville, Kentucky. Skies were clear, winds were light, temperatures hovered near 70 and dew points registered in the 30's. It was the last day in April, 1988, another dry day that concluded another month that went into the records with significantly less than normal monthly precipitation.

At 4:30 that afternoon a call came into the forecast office from Sellersburg state police in southern Indiana. A somewhat shaken voice reported that a tornado had leveled a greenhouse in New Albany, Indiana, five miles northwest of Louisville. Five people were hospitalized as a result of injuries incurred by flying debris as the greenhouse was destroyed. The structure of the greenhouse consisted of cement block and wood with a transparent plastic cover.

Forecasters at the forecast office in Louisville were momentarily without an explanation and quite skeptical of the report on a day when skies were clear across northern Kentucky and southern Indiana. After further description of the event and a close examination of current weather conditions, the staff decided that a whirlwind, most likely a dust devil, had leveled the greenhouse.

2. The Pre-Devil Environment

The single most important element for the formation of dust devils is thermal convection. This whirlwind is spawned by absolute instability in the lowest layers of the atmosphere caused by intense heating of the earth's surface. The lapse rate oftentimes greatly exceeds the dry adiabatic, becoming extremely superadiabatic in a layer from the ground to about 0.5 meters. From 0.5 to 10 meters the lapse rate is strongly superadiabatic with the layer continuing moderately superadiabatic up to about one kilometer.

McClelland, Snow, and Conner (1986), in a study of dust devils, found that when the lapse rate from 0.5 to 10 meters reached a value of approximately 0.25 degrees Celsius per meter the first devils developed. The first occurrences were around solar noon with the activity increasing during mid afternoon as the lapse rate increased to 0.38 degrees Celsius per meter. At that time, the maximum soil surface temperatures and convective heat flux were occurring. The last devils were observed during late afternoon with cessation occurring as the lapse rate decreased to less than 0.25 degrees Celsius per meter.

If the single most important element for the formation of dust devils is thermal convection, then the effects of wind, cloud cover, and topography must be examined. Cloud cover is directly related to the vertical stability of the lower atmosphere. Cloud cover negates the intense heating of the earth's surface needed for strong thermals, thereby acting as a depressing factor on the formation of dust devils.

Wind speed plays an equally important role on dust devil activity. As winds increase, an increase in the vertical mixing of the boundary layer is produced. Sinclair (1969) stated that this weakening of the superadiabatic lapse rate has a dampening effect on dust devil vertical development by shearing off the tops close to the ground. Thus, for this case study, conditions for devil formation were ideal with boundary layer winds of one to ten miles an hour.

Flat surfaces which are the best radiators of heat, such as blacktop and dry, dusty soil, are also best for the formation of dust devils. Surfaces with less ability to absorb heat, such as grasslands, forests, marshes, etc., will produce significantly fewer and weaker thermals.

3. Source of Vorticity

Vorticity, simply meaning the spin of a parcel of air, must be present within a dust devil. The turning motion must be present before the devil vortex develops. Past studies of dust devils have indicated several possible sources of vorticity in the vertical.

Maxworthy (1973) speculates on the source of vertical vorticity dust devil. He states that the horizontal vorticity in the boundary flow is translated into the vertical vorticity. As thermals develop, local low level convergence occurs and any existing ambient vertical vorticity is affected and a vortex is formed. For the vortex to continue and grow, this feed and changeover of horizontal to vertical vorticity must continue.

Carroll and Ryan (1970) speculated that the source for vertical vorticity is created by the strong updrafts from the earth's surface (convective heat transfer in the vertical) and the coinciding downdrafts. The downdrafts, diverging horizontally and asymmetrically, would cause short-lived areas of local horizontal shear thus providing a possible source for vertical vorticity.

4. The Event

On April 30, 1988, a dust devil destroyed a greenhouse five miles northwest of Louisville, Kentucky (Fig. 1). The damage to the greenhouse and its contents was estimated at $4,000. The structure was built on a flat surface covered by blacktop. Directly across the highway was a plowed field surrounded by green vegetation. The damage observed (twisted metal, pieces of wood thrown 100 feet,

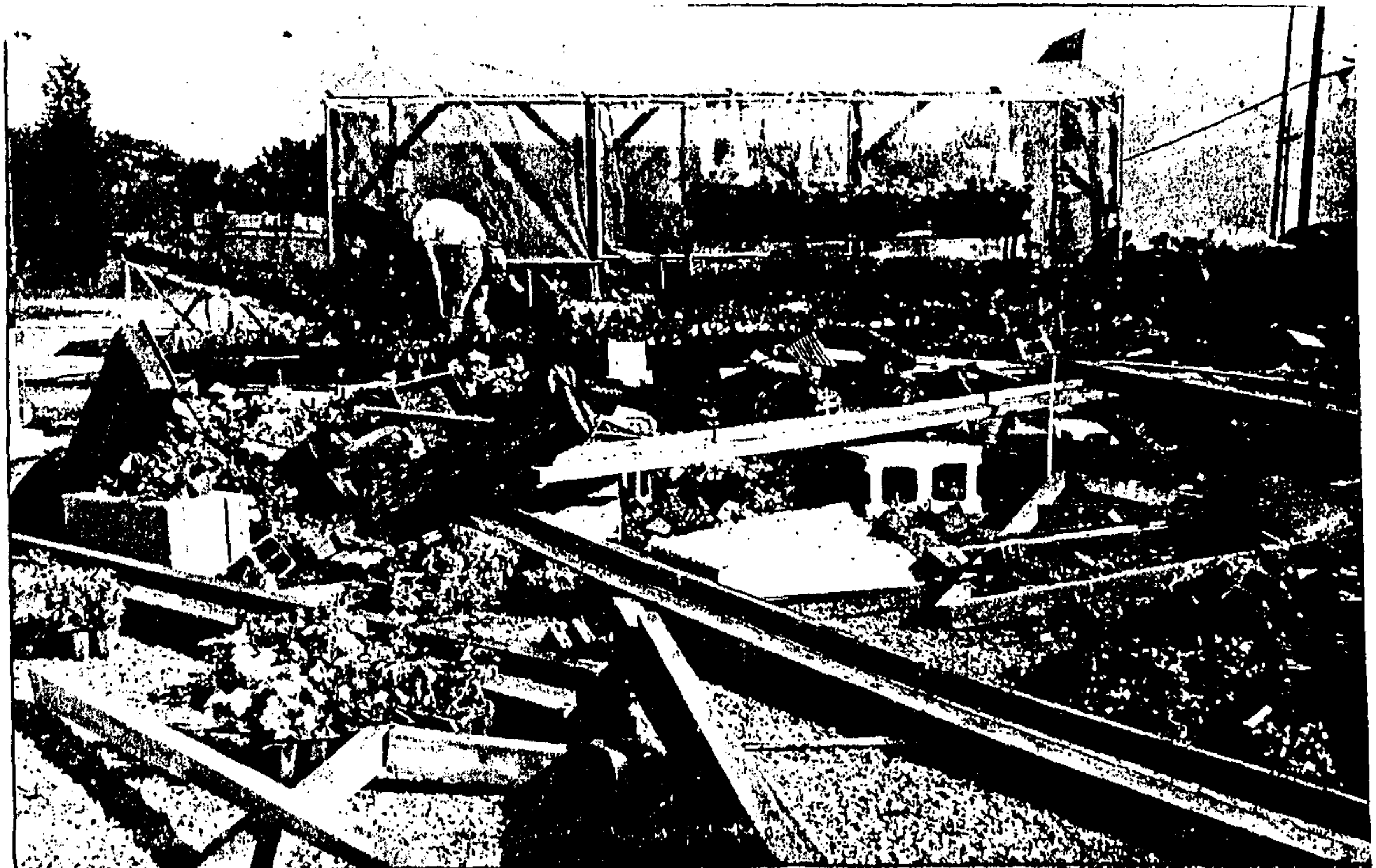

Fig. 1. Shoppers rummage through the debris left after a dust devil destroyed one of two greenhouses at a business in New Albany, Indiana.

plastic and other material wrapped around electrical wires above) indicated wind speeds on either side of the devil in the 50 to 70 mile an hour range.

The owner of the greenhouse, on his way to inspect the damage, noticed empty plant containers from the greenhouse a mile away. Strong vertical motions associated with large dust devils in the deserts of the west have been observed to reach above 5,000 feet, but it is likely that a dust devil in the lower Ohio valley may have vertical motions reaching only from 100 to 200 feet.

5. Weather Analysis

A cool and dry air mass lay over Kentucky on April 30, 1988. Surface high pressure was centered over Illinois (Fig. 2) moving southeast. After an early morning low in the mid-40's, temperatures rose steadily under sunshine to around 70 by mid afternoon, despite weak cold advection. Dew points in the 30's indicated any cumulus development would likely result in less than 5/10 sky coverage with convective temperatures on upstream morning soundings around 70.

By late afternoon, a few cumulus did develop (see SDF observations - Table 1) but the low level air was too dry to support more than a tenth of coverage. The presence of cumulus, despite the low dew points, was a sign of strong thermals and associated vertical lift. The 00Z Dayton sounding that evening (Fig. 3) indicated a strong superadiabatic lapse rate in the lowest layers.

6. Conclusion

A whirlwind reaching destructive force in the lower Ohio Valley is a rare event. The purpose of this paper was to better acquaint those of us in the eastern U.S. to this local warm core, low pressure weather phenomenon, and to provide the elements necessary for its formation.

Very dry soil conditions in much of the eastern U.S. combined with hot but unusually dry air during the spring and early summer of 1988 led to a dramatic increase in the number of whirlwinds reported to the forecast office in Louisville. The whirlwind that developed into an apparent dust devil in New Albany, Indiana, formed on a day when soil conditions were dry, topography in the area was ideal for strong thermals, low level moisture was scant, preventing cloud development, and thus allowing the lapse rate to become strongly superadiabatic in the lowest layers.

7. Acknowledgements

A special thanks to Ernest Goetsch (Lead Forecaster, WSFO Louisville) for his input and encouragement.

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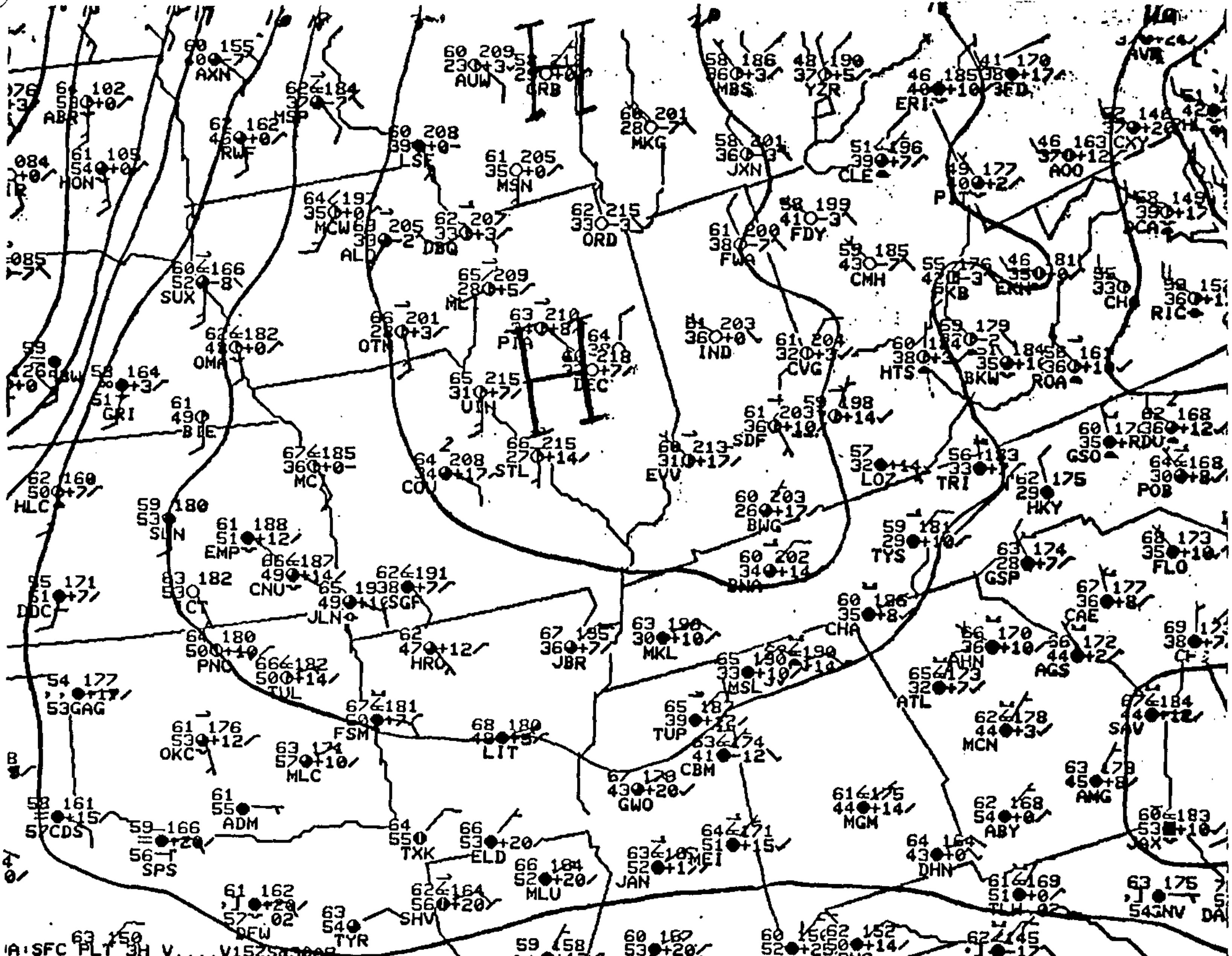

Fig. 2. 15Z surface pressure analysis (every 2 mb.)

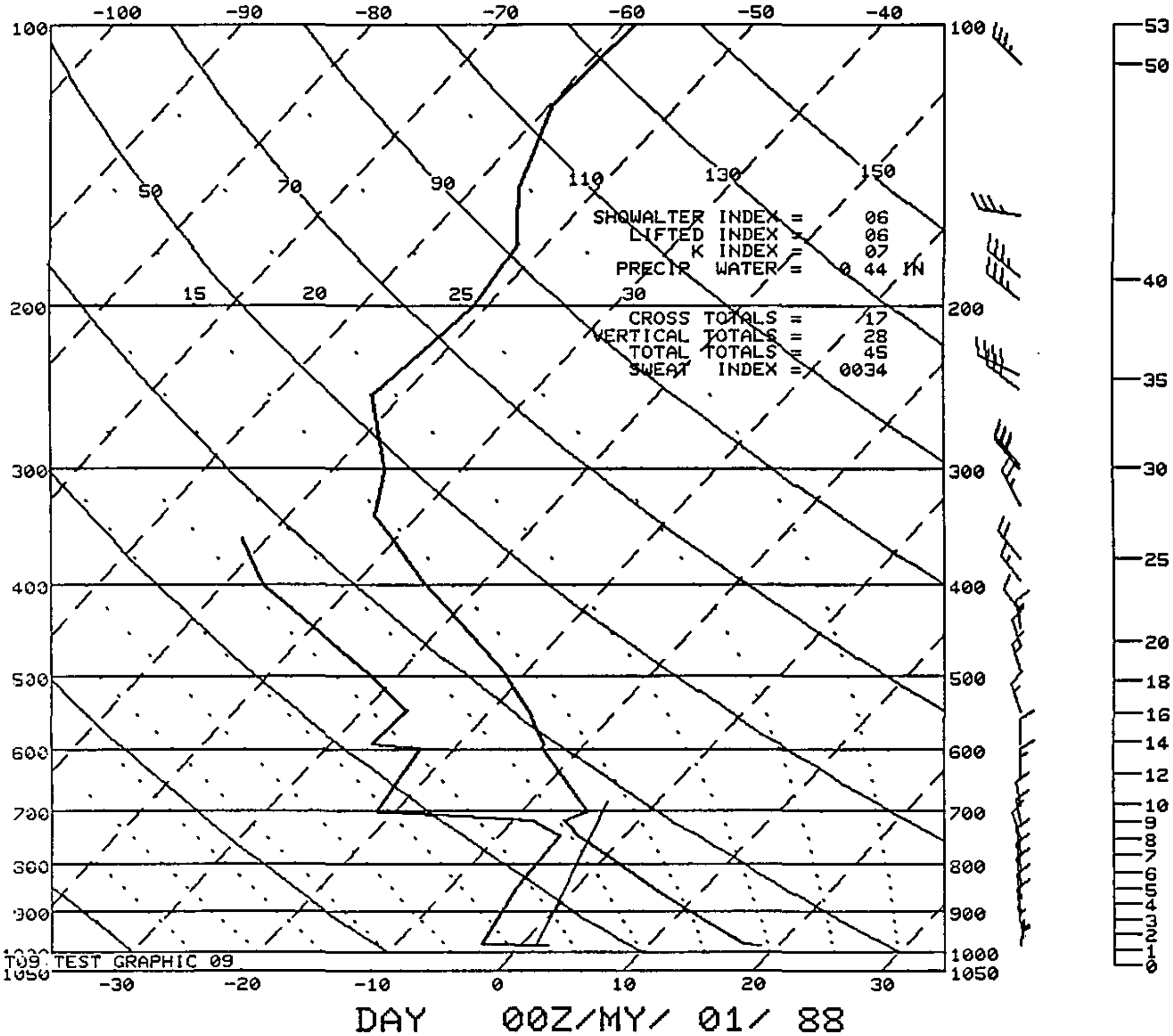

Fig. 3. 00Z May 1, 1988 Dayton, Oh. sounding

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SDF SA 2050 CLR 12 175/70/38/0707/005/FEW CU/ 717 1100
SDFSAOSDF
TTAA00 KSDF 301951
SDF SA 1950 CLR 12 182/71/38/0409/007/FEW CU
SDFSAOSDF
TTAA00 KSDF 301851
SDF SA 1850 CLR 12 189/70/37/0305/009/FEW CI
SDFSAOSDF
TTAA00 KSDF 301750
SDF SA 1750 250 -SCT 12 192/68/36/0606/010/ 810 1001 46946
SDFSAOSDF
TTAA00 KSDF 301653
SDF SA 1650 250 SCT 12 199/66/37/0608/012
SDFSAOSDF
 TTAA00 KSDF 301549
SDF SA 1549 250 SCT 12 206/65/35/0705/014
SDFSAOSDF
 TTAA00 KSDF 301453
SDF SA 1450 250 SCT 12 203/61/36/1706/013/ 210 1008
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Table 1. Hourly observations for Louisville.
Dust devil occurred between the 1950 and 2050 obs.

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