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NOAA Technical Memorandum NWS SR-127

QUALITATIVE ANALYSIS AND FORECASTING OF TORNADIC ACTIVITY USING STORM-RELATIVE ENVIRONMENTAL HELICITY

Gary R. Woodall
National Weather Service Office
Midland, Texas

Scientific Services Division
Southern Region
Fort Worth, Texas
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UNITED STATES DEPARTMENT OF COMMERCE
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ABSTRACT

A set of programs is presented and discussed which, if thunderstorms develop, could be used to analyze and qualitatively forecast the extent of tornado occurrence associated with the thunderstorms. The background concept, storm-relative environmental helicity, is discussed, along with the computer algorithms. Some shortcomings in the programs are given. Verification of the programs in operational case studies is presented and interpreted.

QUALITATIVE ANALYSIS AND FORECASTING OF TORNADIC ACTIVITY USING STORM-RELATIVE ENVIRONMENTAL HELICITY

I. INTRODUCTION

For the past several decades, considerable research time and effort has been spent on thunderstorms. Due to their large size, long life, and ability to produce tornadoes and large hail, supercell thunderstorms have received much of this attention.

By the mid 1960's, researchers had derived the fundamental structure of the supercell thunderstorm (Browning and Donaldson, 1963). That is, supercells were found to consist of a single, long-lived, rotating cell which propagated to the right of the mean tropospheric winds. During the early and mid 1970's, Doppler radar analyses documented the formation and evolution of the mesocyclone (Lemon et al., 1978). These analyses also indicated that supercells were not entirely steady-state, as small-scale variations in the reflectivity and wind fields were detected.

In addition, researchers had determined the fundamental surface and upper-air patterns associated with severe thunderstorms. Researchers demonstrated the relationship between severe storms and upper-level wind features (Uccellini and Johnson, 1979), various surface boundaries (Berry, 1981; Rhea, 1966), and thermodynamic profiles (Carlson and Ludlam, 1968). For additional discussion, see Doswell's (1982,1985) comprehensive reviews on analysis of severe thunderstorms and their mesoscale environments.

By the mid 1980's, numerical models accurately depicted the formation of storms and their associated wind fields (Weisman and Klemp, 1982,1984). These studies supported the theory that there was a spectrum of storm types, with short-lived single cells, multicell complexes, and supercells being the main storm classifications. Weisman and Klemp (1982) found that the characteristics of a particular storm were dependent on the magnitudes of instability and environmental wind shear which were present. It was determined that multicell storms existed in environments of high instability and small vertical shear of the horizontal wind. On the other hand, supercells tended to form in environments with moderate to high instability and large vertical shear of the horizontal wind.

Weisman and Klemp (1984) expanded upon their earlier work by running another series of simulations whose environments had directionally-varying wind fields. These simulations basically supported their earlier results, and explained why, in typical severe convective events, the right moving component of a split cell is the one usually favored for prolonged existence.

The results of these (and many other) research efforts indicate the following:

1) For convection to occur, an unstable atmosphere, adequate low-level moisture, and a trigger mechanism are required.

2) Long-lived storms require a balance between atmospheric instability and vertical shear of the horizontal wind (i.e., a favorable bulk Richardson number).

3) Storm rotation requires strong veering of the storm-relative horizontal wind in the lowest few kilometers.

Recent analysis programs such as ADAP (Bothwell, 1988) have proven beneficial in forecasting the development of convection (Point 1 listed above). In this work, a set of programs is described which, given thunderstorm occurrence, analyze and forecast the conditional possibility or extent of storm rotation (Point 3 listed above). This is done using the concept of storm-relative environmental helicity. The above-mentioned programs are called HAFP (Helicity Analysis and Forecast Programs).

If HAFP proves successful, it would be a benefit to National Weather Service forecasters. At the WSO and WSFO levels, the early forecasting of possible tornadic activity within a station's area of warning responsibility would allow extra personnel and spotter networks to be activated and in place well before the convection began. At the national (SELS) level, HAFP would give forecasters another tool to use in evaluation of the tornado threat. This would help forecasters in isolating potential problem areas, and increase their confidence in the issuance of watch boxes and outlook areas.

Once the restructuring of NWS is complete, and the NEXRAD and wind profiler networks are installed, NWS personnel will have wind data available with greater temporal resolution. A program such as that outlined in this work could be incorporated as an algorithm for use with profiler or NEXRAD clear-air data. The wind field could then be monitored hourly (or as often as wind data became available) for increasing or decreasing rotation potential in the environment.

Section II of this work is devoted to the mathematical and physical background of HAFP, and Section III discusses the actual program algorithms. Section IV presents some limitations inherent in programs of this type, and Section V discusses case studies from late 1988 and the spring of 1989. Section VI contains a summary and discussion.

II. MATHEMATICAL AND PHYSICAL BACKGROUND

Lilly (1986) suggested that the longevity of supercell storms is due to high positive values of helicity. Helicity is properly defined as the volume integral of the dot product of the velocity and vorticity vectors:

$$H = \int_v \vec{V} \cdot \vec{\omega} \, dv$$

where $\vec{V}$ is the 3-dimensional velocity vector and $\vec{\omega}$ is the 3-dimensional vorticity vector. Since we are interested in obtaining helicity values for (essentially) point locations, we can define a "local" helicity as:

$$h = \vec{V} \cdot \vec{\omega}$$

Brandes <u>et al.</u> (1988) noted that since helicity is not Galilean invariant (it is dependent on the reference frame), storm-relative helicity is the only physically meaningful measure of helicity. To calculate this, we define the storm motion vector as $\vec{C}$ such that

$$\vec{V_s} = \vec{V} - \vec{C}$$

Operationally, this poses the biggest problem for the programs. The storm motion vector must be known or well-approximated before values could be calculated. Now, the storm-relative helicity becomes

$$h = \vec{V_s} \cdot \vec{\omega}$$

which can be rewritten as

$$h = u_s\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right) - v_s\left(\frac{\partial w}{\partial x} - \frac{\partial u}{\partial z}\right) + w_s\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \qquad [a]$$

In the pre-convective environment (or in the relatively undisturbed environment near a storm), we can assume $w \ll u$ and v, and let w approach 0. Also, we can assume u and v will be nearly constant horizontally over our area of consideration (i.e., the area within about 100 km of an analysis or forecast location). Thus, (a) reduces to

$$h = v_s \frac{du}{dz} - u_s \frac{dv}{dz}$$

Physically, then, helicity may be viewed as the product of the strength of the storm-relative horizontal wind and the veering of the storm-relative horizontal wind. Figure 1 shows that, for a clockwise-turning hodograph (typical for a tornado event), the storm-relative helicity must be positive.

Lilly (1983), and Davies-Jones (1984) also stated that when helicity values are high, the horizontal vorticity in the storm's

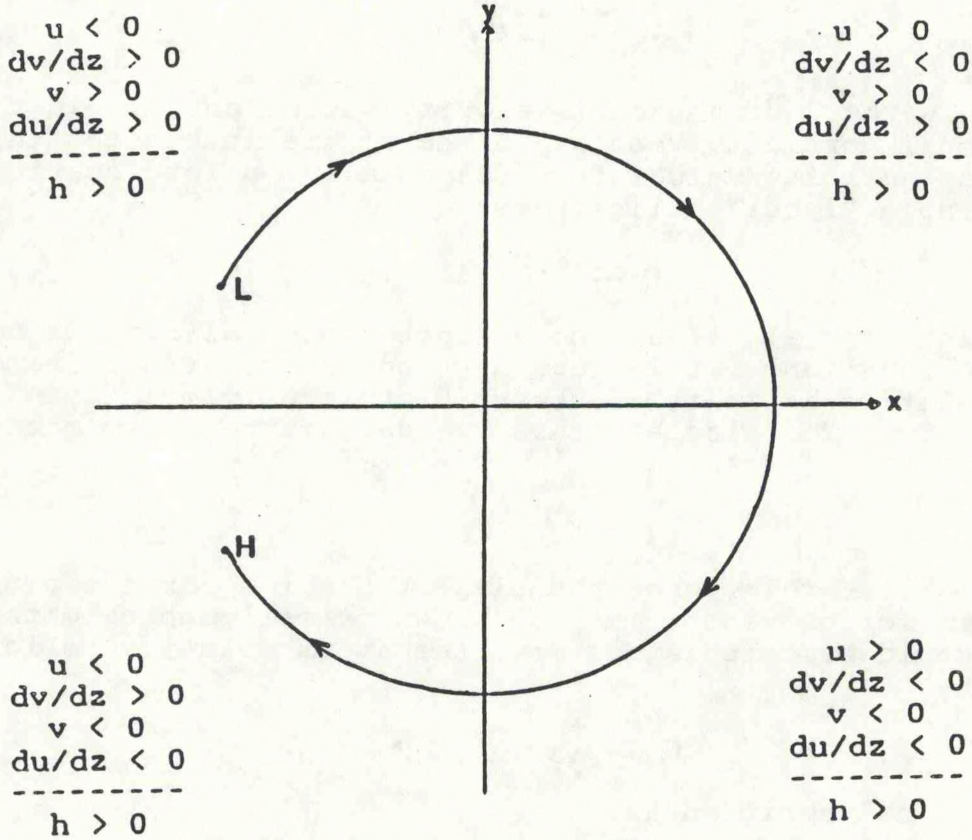


FIGURE 1: Simplified clockwise-turning hodograph. In each quadrant, the sign of each component of the horizontal helicity formula is evaluated, demonstrating that a clockwise-turning hodograph does have positive helicity.

inflow region tends to be streamwise (i.e., the vorticity vector is aligned with the velocity vector). Barnes (1970) suggested that this component of vorticity is tilted by the updraft to generate cyclonic vorticity on the updraft's upstream side. Davies-Jones (1985) deduced that supercells are thus able to convert some of the large positive horizontal helicity in the environment (which we calculate here) into the vertical helicity necessary for storm longevity and rotation.

Davies-Jones (1984) proved that if the vorticity is streamwise, there will be a high correlation between the centers of vertical vorticity and vertical velocity. In other words, an environment with high helicity (vorticity which is primarily streamwise) favors the development of cyclonically rotating updrafts and anticyclonic downdrafts. These features have been documented in various Doppler radar studies (Ray et al., 1980; Woodall and Bluestein, 1988). Davies-Jones et al. (1984) adopted the formula for the calculation of the vertical velocity/vertical vorticity correlation coefficients into a prototype short-term forecasting model for thunderstorm rotation. Note, though, that the work described here differs from Davies-Jones et al. in that we calculate and forecast actual helicity values rather than correlation coefficients.

To further illustrate the close relationship between helicity and streamwise vorticity, consider a simplified case as shown in figure 2. Winds are from the east at level 1 (lower levels), from the south at level 2 (mid levels), and from the west at level 3 (upper levels). If we calculate the three-dimensional vorticity using a finite difference scheme at level 2, we get

$$\vec{\omega} = \frac{du}{dz}\hat{j}$$

Note that this vector, pointing in the $\hat{j}$ direction, is parallel to the velocity vector at level 2. This means that the vorticity at level 2 is streamwise.

Recall our formulation for local helicity:

$$h = \vec{V} \cdot \vec{\omega}$$

The dot product can be rewritten as

$$h = |\vec{V}||\vec{\omega}|\cos\theta$$

where the braces indicate the magnitude (length) of the vector, and θ is the angle between the vectors. In this example, $\theta=0$, so

$$\cos\theta = 1$$

and h will be a maximum.

Summarizing all of this, an environment in which the storm-

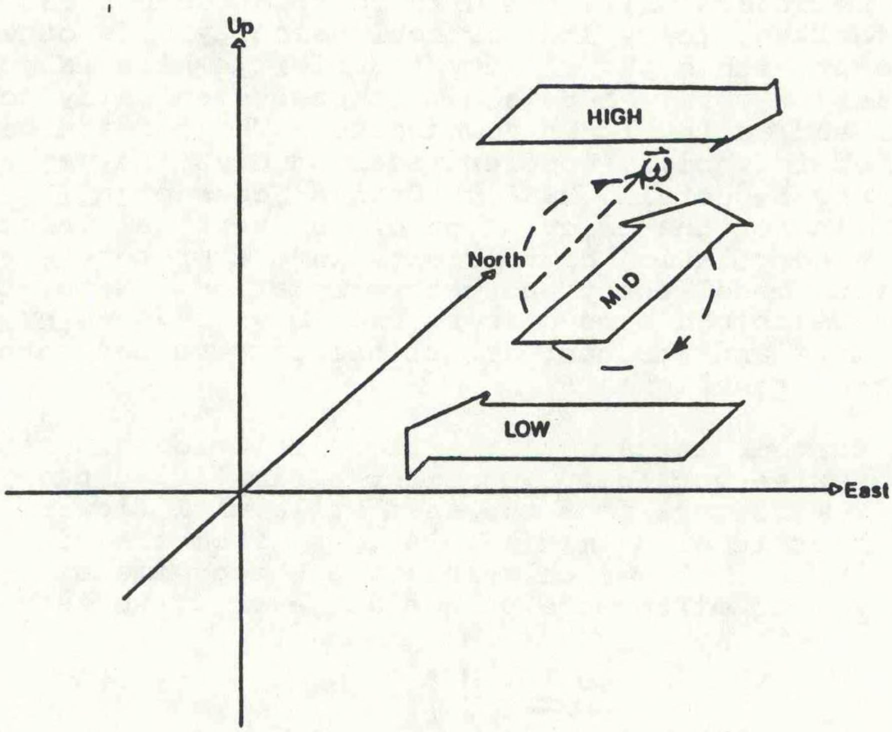


FIGURE 2: Simplified veering wind environment. Broad arrows indicate (storm-relative) wind flow at low, mid, and high levels. Dashed circle represents horizontal vortex formed in this environment. Dashed arrow represents horizontal vorticity vector.

relative horizontal wind is strong, and veers in the lowest few kilometers, has a large positive helicity value. The actual value of helicity will be determined by the strength and amount of veering of the winds. In such a veering-wind environment, the horizontal vorticity is primarily streamwise, and a high correlation exists between the centers of vertical velocity and vertical vorticity. Conversely, if the storm-relative environmental winds back with height, the helicity value is negative, and vertical velocity and vertical vorticity are negatively correlated (that is, anti-cyclonically rotating updrafts and cyclonically rotating downdrafts will be favored).

Thus, if there were a way to calculate (or forecast) the helicity (storm-relative) in the lowest few kilometers of the storm's environment, one might predict the possibility and character of tornadic activity (given that thunderstorms form).

III. THE PROGRAMS

There are two programs in HAFP. These programs reside on floppy disk for use in the Auxiliary/Backup Terminal (ABT) computer, an IBM PC which serves as an additional or backup AFOS terminal, depending on station needs. This design was chosen for two reasons: 1) Under normal operating conditions, the programs can be run without affecting AFOS operations. 2) If a station's AFOS equipment were to become inoperable, the programs could still be run without adversely affecting the backup computer. The first program (HAFP-1) does a detailed analysis and/or 12-hour forecast of a single upper-air station's helicity values for a variety of storm motion vectors. The second program (HAFP-2) calculates a severe storm motion vector for locations in a four to eight state geographical area, and calculates forecast helicity values at 6-, 12-, or 24 hours for these sites. The programs' internal workings are outlined below.

In HAFP-1, a subroutine first reads in wind data from the significant levels PPBB message. These data are decoded and passed on to the main program. The wind data are analyzed to 2000-foot levels using a Cressman analysis scheme with a radius of influence varying from 4000 to 6000 feet, depending on the height of the wind data level. The mean wind from the surface to 36000 ft AGL is calculated. Using climatological values (adapted from Bluestein and Parks, 1983), a severe storm motion speed and direction are predicted. Since the actual storms may have different cell movements from what was predicted, storm-relative winds are calculated for several azimuth angles near the predicted severe storm azimuth, and for speeds from 10 to 50 knots. These storm-relative winds are used to calculate helicity values for the above-mentioned storm motions.

If a 12-hour helicity forecast is desired as well, wind data are input from the LFM-based aviation winds aloft forecast (FD2). This product gives forecast wind direction and speed beginning no higher than 3000 feet AGL. Wind forecasts are given at 3000 foot levels to 12000 feet MSL, then at 4000 to 6000 foot levels to 39000 feet MSL. An empirical formula for Ekman turning in the boundary layer (Holton, 1979) is used to calculate the predicted surface wind from the lowest available level in the winds aloft forecast. From here, the program proceeds as above.

Finally, the program prints all computed data and suggests interpretation of the calculated helicity values.

HAFP-2 inputs the winds aloft forecast data, one station at a time. For each station, a mean wind from the surface to 36000 feet is calculated using the same techniques as in HAFP-1. A severe storm motion is predicted based on this mean wind, and storm-relative winds are computed using this severe storm motion. The relative helicity is then calculated for the station, and the cell motion and forecast helicity are plotted on the appropriate map background.

The forecast domain for HAFP-2 is an area which covers roughly the central one-third of the United States - the area most prone to supercell storms and significant tornado events. This area runs from Alabama to Indiana, northwest to North Dakota, south to Texas, and east to Alabama. See figure 3 for the outline of this area.

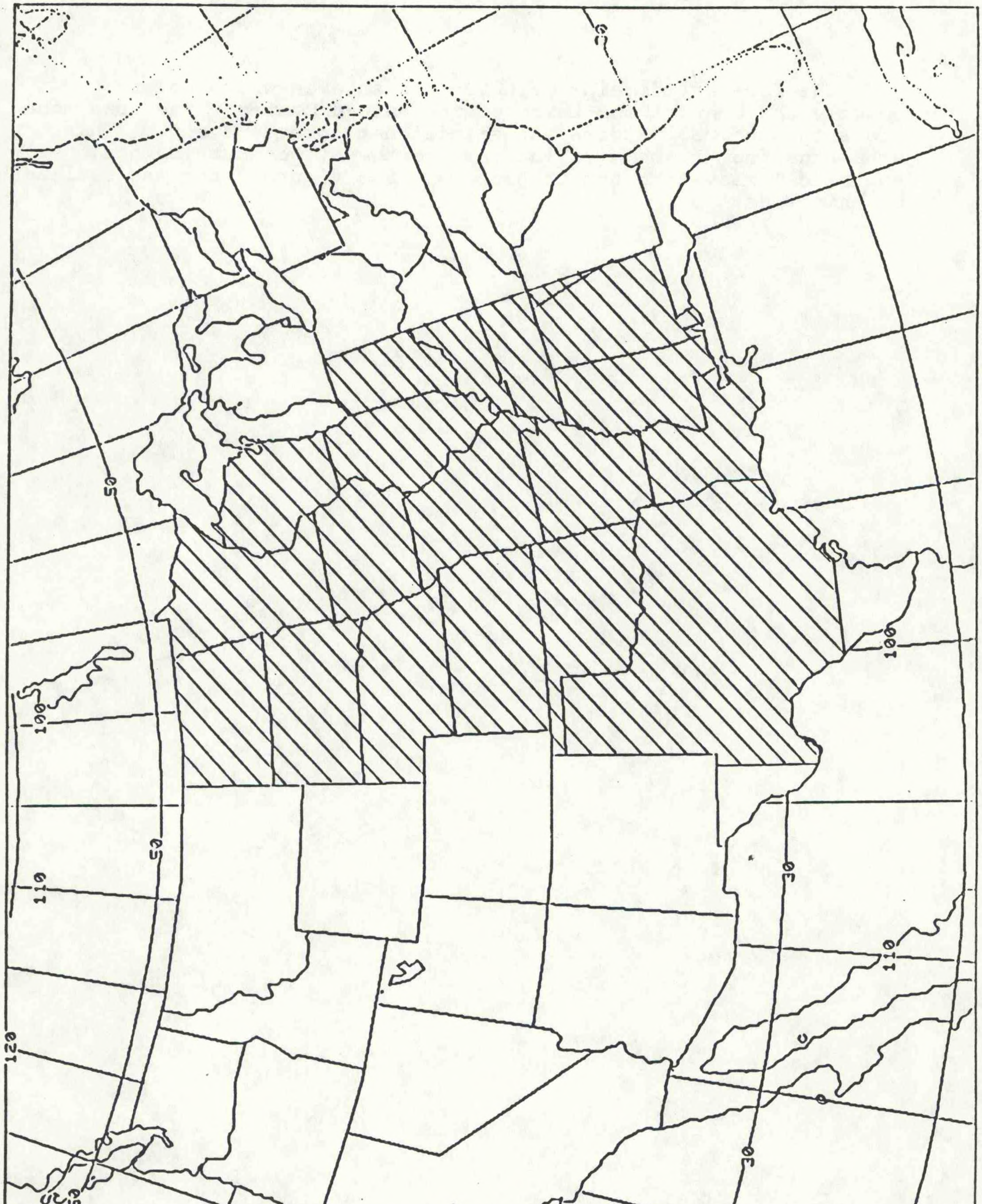


FIGURE 3: Outline of forecast domain for regional helicity forecasting program (HAFP-2).

IV. LIMITATIONS OF THE PROGRAMS

There are a number of items, both conceptual and operational, that may limit the effectiveness of these programs. First, it should be emphasized that we are using synoptic scale data to attempt to predict a mesoscale (or microscale) event. Bluestein et al. (1988) demonstrated that even in cases where the environment may be favorable for deep convection and severe weather, actual tornado occurrence may be localized within that area.

Second, these programs can not and should not replace a careful examination of of the pertinent soundings, analyses, and forecasts. Rather, these programs should be used as another tool to evaluate the tornado threat.

Third, it is uncertain if the winds aloft forecast has a fine enough vertical resolution to generate consistently accurate helicity values. The typical PPBB message gives winds every 1000 to 2000 feet. The winds aloft forecast gives wind data every 3000 feet for altitudes below 12000 feet MSL, and every 4000 to 6000 feet for altitudes above 12000 feet. Some of the structure of the hodograph below 12000 feet (which is most important for helicity calculation) may be lost through this lack of vertical resolution, and inaccurate helicity forecasts may result.

It appears that this concern may be unfounded. Three different wind hodographs were constructed (not shown) from a storm-environment sounding taken in Oklahoma during the afternoon of 26 April 1984. One hodograph contained only the raw wind data. The second was made using the observed data objectively analyzed to 2000 foot levels (as done in HAFP). The third hodograph was constructed using objectively-analyzed data, but the input data was restricted to the levels available in the aviation winds aloft forecast. The hodographs appeared quite similar, and were nearly identical in the important 0 to 4 kilometer layer.

Fourth, it should be emphasized again that this program can not forecast whether or not thunderstorms will occur! Instead, it will only analyze and predict the "rotation potential" of the storm environment, assuming thunderstorms do form. Products such as ADAP and/or the SELS convective outlook should be used to diagnose the probability of thunderstorm formation (i.e., areas of instability, low level moisture and moisture convergence, etc.). Once an area of probable thunderstorm formation has been located, HAFP should be employed to determine the probability of tornado occurrence within this region.

Fifth, the analysis portion of HAFP-1 can be run as soon as the SGL messages are sent (usually just after 1200Z and 0000Z). The forecasts cannot be made, though, until the FD2 messages are sent from NMC. This usually occurs at about 1630Z to 1645Z for the 12Z run, and about 0430Z to 0445Z for the 00Z run. On days when convection breaks out early, this may be too late for practical use.

Sixth, these programs will be most useful when attempting to predict mesocyclone-produced tornadoes under synoptically-favorable conditions. Events such as "landspout" type tornadoes (Bluestein, 1985), tornadoes produced primarily by smaller-scale processes (e.g. locally backed winds associated with a subsynoptic low) and the "marginal" severe weather event (Moller and Ely, 1985) may not be handled well by these programs.

V. CASE STUDIES FROM LATE 1988 AND SPRING 1989

From mid November 1988 to mid June 1989, a total of 19 severe weather events were utilized as cases to test HAFP. What follows is a tabular summary of these 19 cases, along with verification statistics. A more detailed look at selected case studies then follows. The atmospheric conditions on the day of the event are presented, along with a look at the helicity forecasts and the day's designated "tornado outlook area". A review of the location and extent of tornadic activity (if any) which occurred completes each case study.

For the purposes of these case studies, the "tornado outlook area" was determined as follows. First, the area of greatest severe thunderstorm risk on the 15Z or 19Z SELS convective outlook was located. Second, the area of high helicity was defined as the area within and 40 miles outside of the 35 x 10^{-3} ms^{-2} isopleth on the helicity forecast map (this allowed for errors in location of the above-mentioned isopleth, and for any mesoscale influences acting on marginally high helicity values). Finally, the "tornado outlook area" was said to be the intersection of the greatest severe thunderstorm risk and high helicity areas.

Values for the verification statistics were defined as outlined below. For the Probability of Detection (POD), a tornado reported in the "tornado outlook area" was considered a "warned event". All tornado reports were the "total number of events". For the False Alarm Ratio (FAR), a WSFO forecast area which had at least one forecast zone included in an outlook area was defined as a "warned area". "Warned" WSFO areas with no tornado reports were considered "unverified areas".

These cases (not including the anomalous event of 4 May) produced a total of 205 reported tornadoes, of which 181 were reported in tornado outlook areas. This gave a Probability of Detection (POD) (Leftwich, 1988) of .883. Of the 61 WSFO forecast areas which were outlooked for tornadic activity, 23 did not verify with a tornado report. The resulting False Alarm Ratio (FAR) was .377. The Critical Success Index (CSI) was .576.

Recent SELS verification statistics for their Severe Weather Outlook areas (Leftwich, 1988) indicate a POD of around .58, a FAR of approximately .60, and a CSI of roughly .25. The HAFP verification statistics appear considerably higher; however, this is not an entirely fair comparison. SELS must provide severe weather outlooks daily, while HAFP was run only when severe convection was a good bet. Additionally, as was pointed out above, the SELS outlooks were used to help delineate the HAFP tornado outlook areas. Nevertheless, the verification statistics indicate the potential value of HAFP as a tool in forecasting tornadic activity.

HAFP CASE STUDIES -- 1988-1989

DATE	TORNADOES OUTLOOKED? (MAXIMUM HELICITY)	TORNADOES WITHIN OUTLOOK AREA	TORNADOES OUTSIDE OUTLOOK AREA	WSFO AREAS OUTLOOKED	WSFO AREAS NOT VERIFIED
11/15	YES(84.5)	43	1	8	1
3/27	NO(15.1)	0	0	0	0
4/3	YES(71.9)	24	0	10	3
4/18	NO(5.2)	0	0	0	0
4/20	YES(45.6)	0	0	3	3
4/26	NO(29.6)	0	6	0	0
5/2	YES(72.4)	3	0	3	2
5/4	ANOMALOUS EVENT -- SEE DETAILED DISCUSSION BELOW				
5/6	NO(28.3)	0	0	0	0
5/8	YES(66.1)	3	0	6	3
5/12	NO(27.2)	0	4	0	0
5/15	YES(47.4)	7	2	2	0
5/16	YES(60.9)	15	2	3	1
5/17	YES(61.0)	23	3	3	1
5/24	YES(72.2)	28	3	6	2
5/25	YES(65.0)	12	0	9	6
6/3	YES(39.2)	6	1	1	0
6/6	YES(68.3)	13	1	3	0
6/11	YES(36.6)	4	1	4	1
TOTALS		181	24	61	23

$$POD = \frac{\text{"WARNED EVENTS"}}{\text{"TOTAL EVENTS"}} = \frac{181}{205} = .883$$

$$FAR = \frac{\text{"UNVERIFIED AREAS"}}{\text{"WARNED AREAS"}} = \frac{23}{61} = .377$$

$$CSI = ((POD)^{-1} + (1-FAR)^{-1} - 1)^{-1} = (1.132 + 1.605 - 1)^{-1} = .576$$

1. 15 NOVEMBER 1988

The tornado outbreak of 15 November 1988 provided an excellent opportunity to test HAFP. The case was unusual for so late in the year, with a high risk of severe thunderstorms forecast by SELS for an area from northeastern Texas into Iowa and Illinois. Ample low-level moisture was drawn northward in advance of a major upper-level storm, setting the stage for the convective activity which was to occur. The fact that the atmosphere was thermodynamically favorable for convection over a large area, while a variety of wind profiles were present, made this an especially appealing case.

A. The 12Z Helicity Analysis

Analyses using HAFP-1 were made for upper-air stations which were in or near the 12Z high risk area: Longview and Stephenville, Texas; Oklahoma City, Oklahoma; Topeka, Kansas; and Monett, Missouri. The results of these analyses are shown on figure 4. The 12Z HAFP-1 analysis shows that the only area in which HAFP-1 indicated a chance of tornado activity was in Oklahoma. Thus, Oklahoma was the only area outlooked for tornado occurrence early in the day.

Figure 5 shows the locations and approximate times of tornado reports from 12Z, 15 November 1988, to 12Z, 16 November 1988. The only tornado activity which occurred before 18Z was observed in Oklahoma, the only area in which HAFP-1 indicated tornado potential.

B. The 00Z helicity forecast

Helicity forecasts valid 00Z, 16 November 1988 were made using HAFP-1 for several selected stations in and near the 19Z severe thunderstorm risk area (HAFP-2 had not been developed at this time, so complete regional forecasts were unavailable). The dryline had already moved east of an OKC-DFW line, so forecasts were not made for locations in central Oklahoma or north central Texas. The results of these forecasts appear on figure 6. The forecast placed the area of tornado possibility from near College Station, Texas to south of Des Moines, Iowa. Very high helicity values were noted in west central Arkansas.

Again consulting figure 5, we see that nearly all of the tornadoes occurred in the region of predicted activity. A grouping of tornado reports is seen in conjunction with the high helicity values in Arkansas. Thus, HAFP correctly forecasted the location and extent of the tornadic activity on this rather remarkable day.

FIGURE 4: Results of HAFP-1 analyses valid 12Z, 15 November 1988. Values use predicted severe storm motion as calculated by HAFP-1.

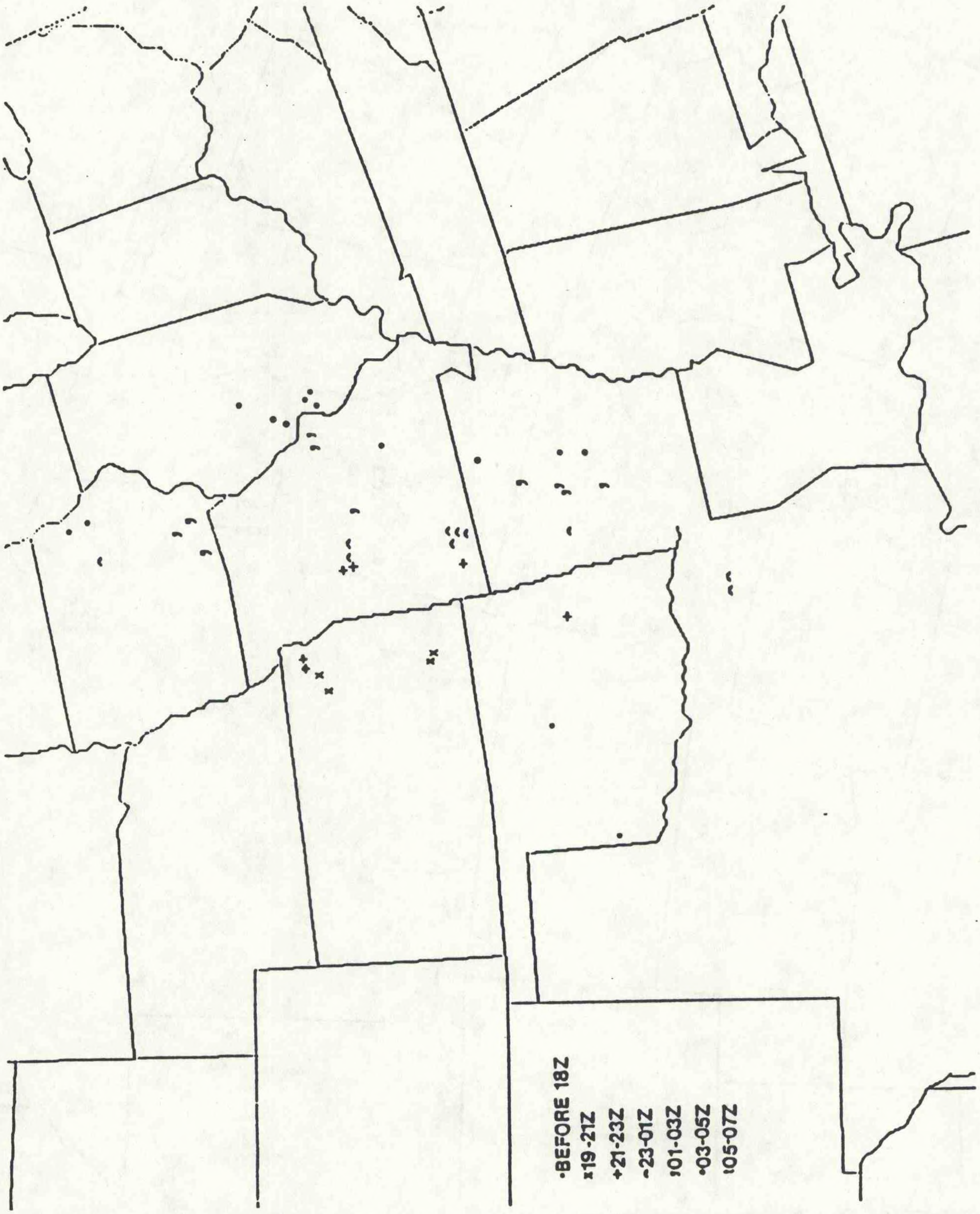


FIGURE 5: Locations and approximate times of tornadoes reported between 12Z, 15 November 1988 and 12Z, 16 November 1988.

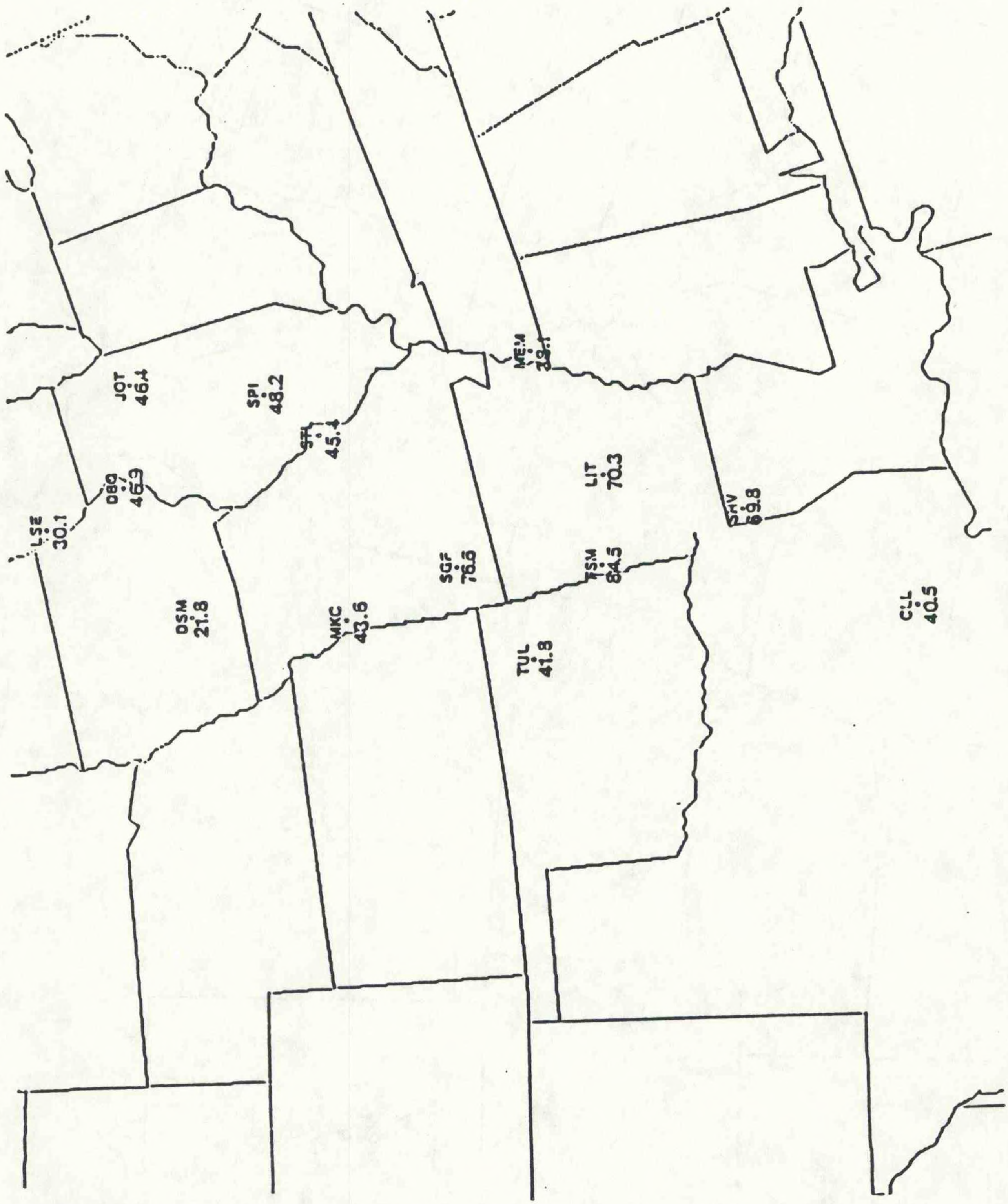


FIGURE 6: Results of HAFP-1 forecasts valid 00Z, 16 November 1988. Values use predicted severe storm motion as calculated by HAFP-1.

2. 3 APRIL 1989

At 12Z, the environment was conducive to deep convection across much of the lower Mississippi and Ohio River Valleys. Temperature differences between 850 and 500 mb were 26-30 degrees C across the region (consult figure 7), with adequate moisture present in the lower levels. Winds at 850 mb were 20-30 knots from the southwest, with westerly winds of 45-60 knots at 500 mb. An area of diffluence was present over the South Central States.

The forecast models indicated a surface cold front moving into the unstable airmass by 00Z, 4 April. Several small vorticity maxima were forecast to rotate through the 500 mb trough centered over the eastern Great Plains. The helicity forecast (figure 8) indicated a band of high helicity along and ahead of the front. Combining the SELS outlook with the helicity forecast, the tornado outlook area was delineated from northeastern Texas to southern Indiana (figure 9). Although no forecast helicity values were above 80, the large number of values in the 60s and 70s suggested the potential for a significant outbreak of tornadoes.

During the late afternoon and evening, 24 tornadoes were reported from northeast Texas to western Kentucky (figure 9). All of the tornadoes were reported in the tornado outlook area. As in the 15 November 1988 case, the helicity forecast successfully indicated the location and extent of tornadic activity.

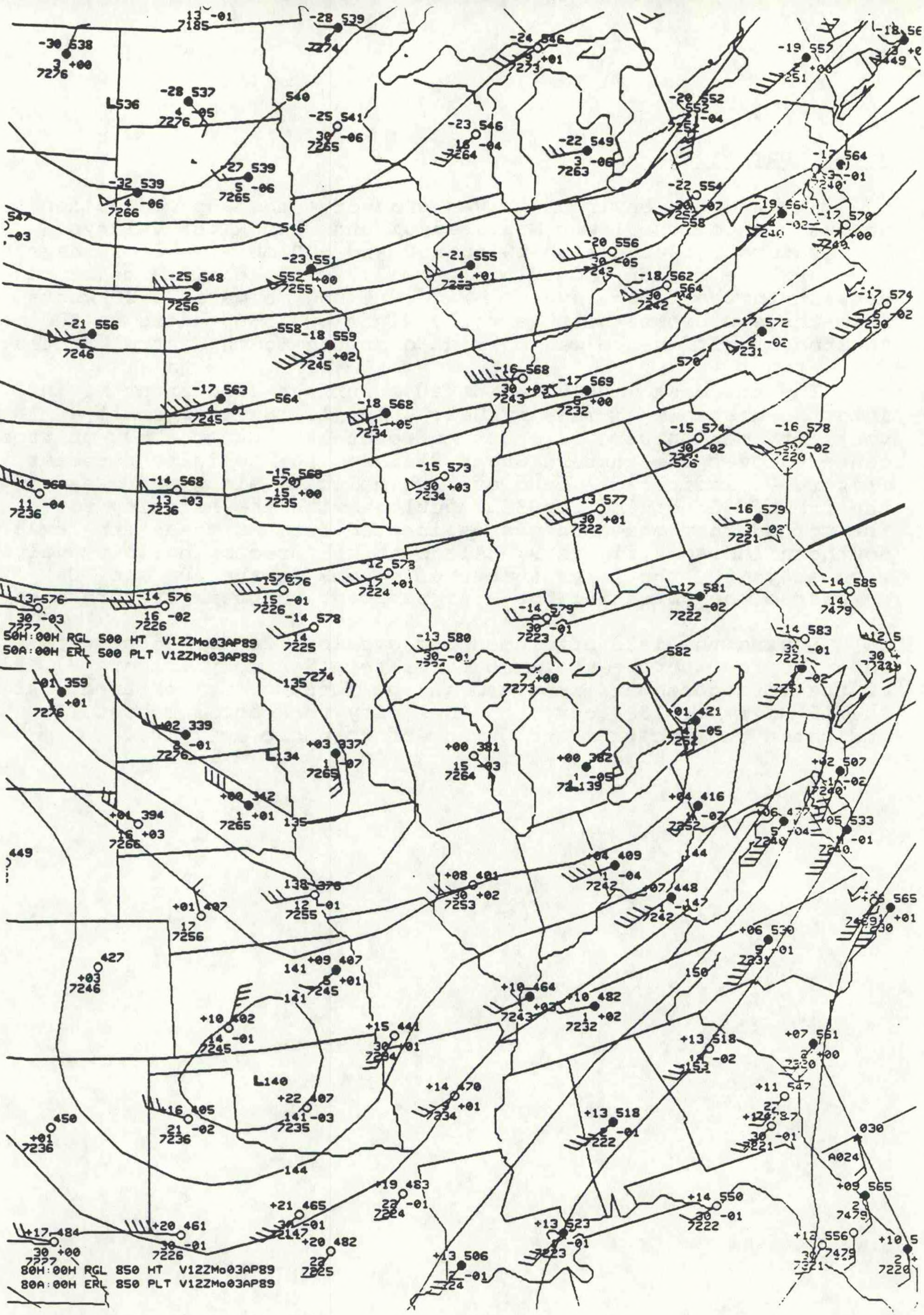
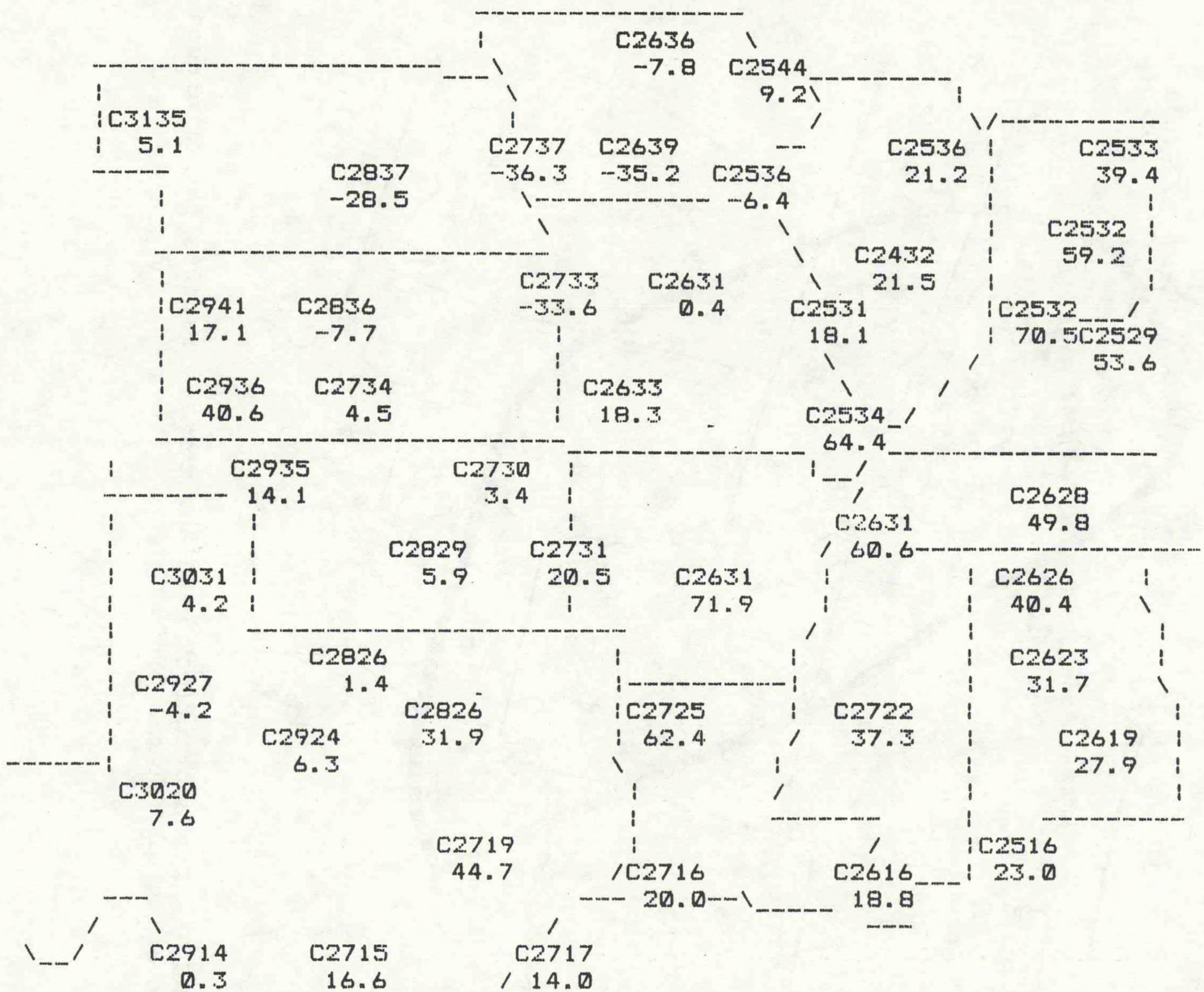


FIGURE 7: 500 mb (top) and 850 mb (bottom) analyses for 12Z, 3 April 1989.



HELICITY FORECAST VALID 04/0000Z

FIGURE 8: Helicity forecast valid 00Z, 4 April 1989. For each station, the predicted cell motion (top) and forecast helicity value (bottom) are displayed.

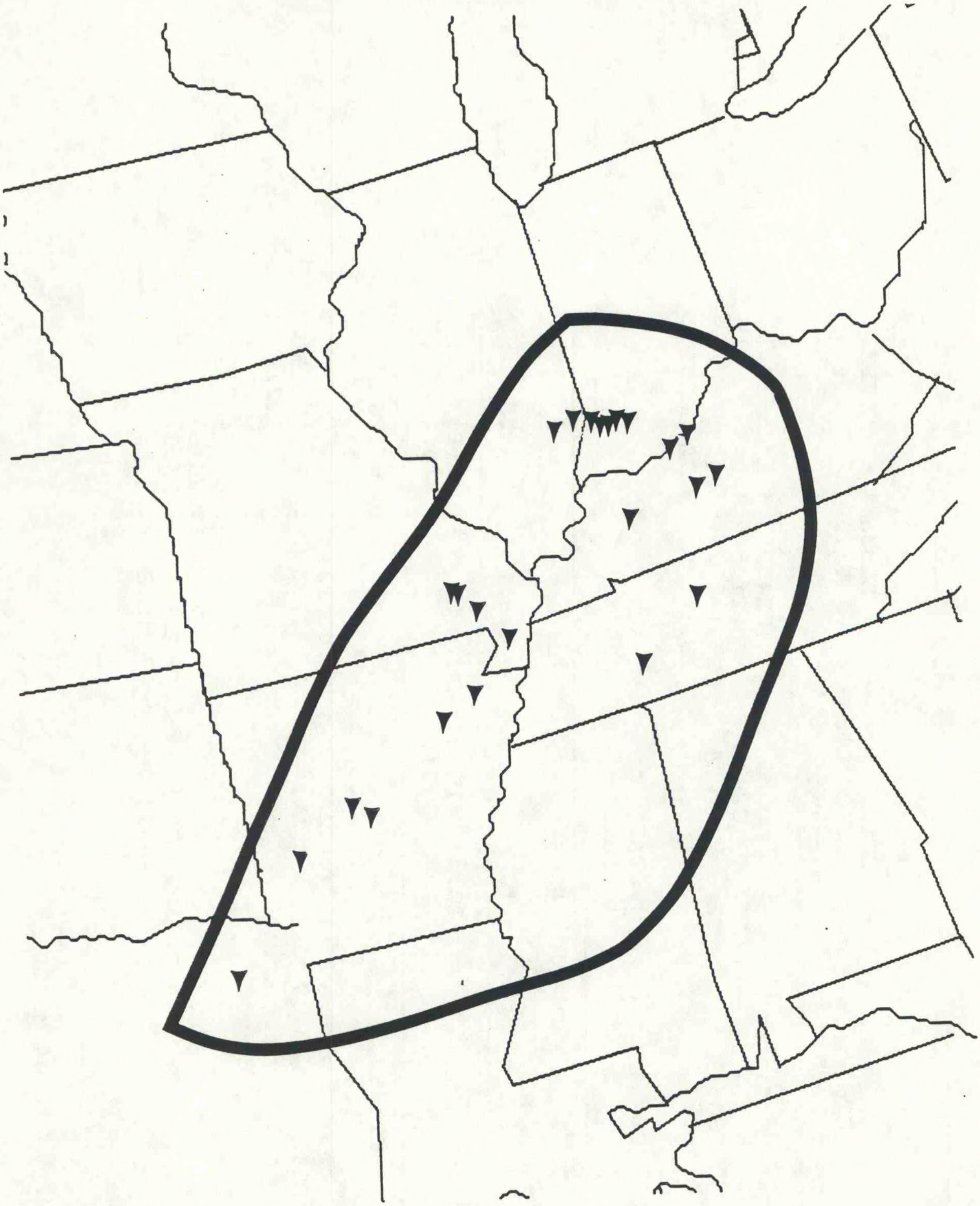


FIGURE 9: Tornado outlook area and tornado reports for afternoon and evening of 3 April 1989.

3. 18 APRIL 1989

This was one of a number of northwesterly flow events to occur over the southern Plains in April. The atmosphere was again very unstable, with 850-500 mb temperature differences near 30 degrees C over Oklahoma, Arkansas, and southwest Missouri (figure 10). Low level moisture was adequate although not spectacular. Winds at 850 mb were from the southwest at 20 knots, and 500 mb winds were west-northwesterly at 30-40 knots.

The numerical forecasts moved a weak vorticity maximum into Arkansas by 00Z, 19 April, and a stronger vorticity maximum into eastern Kansas. Low-level winds were forecast to weaken slightly. The helicity forecasts indicated low values (figure 11), and little chance of storm rotation was forecast.

During the afternoon and evening, large hail (up to golfball size) was reported across eastern Oklahoma and western Arkansas. Damaging winds downed trees and power lines in western Arkansas, but no tornadoes were reported. Thus, HAFP correctly predicted no significant storm rotation.

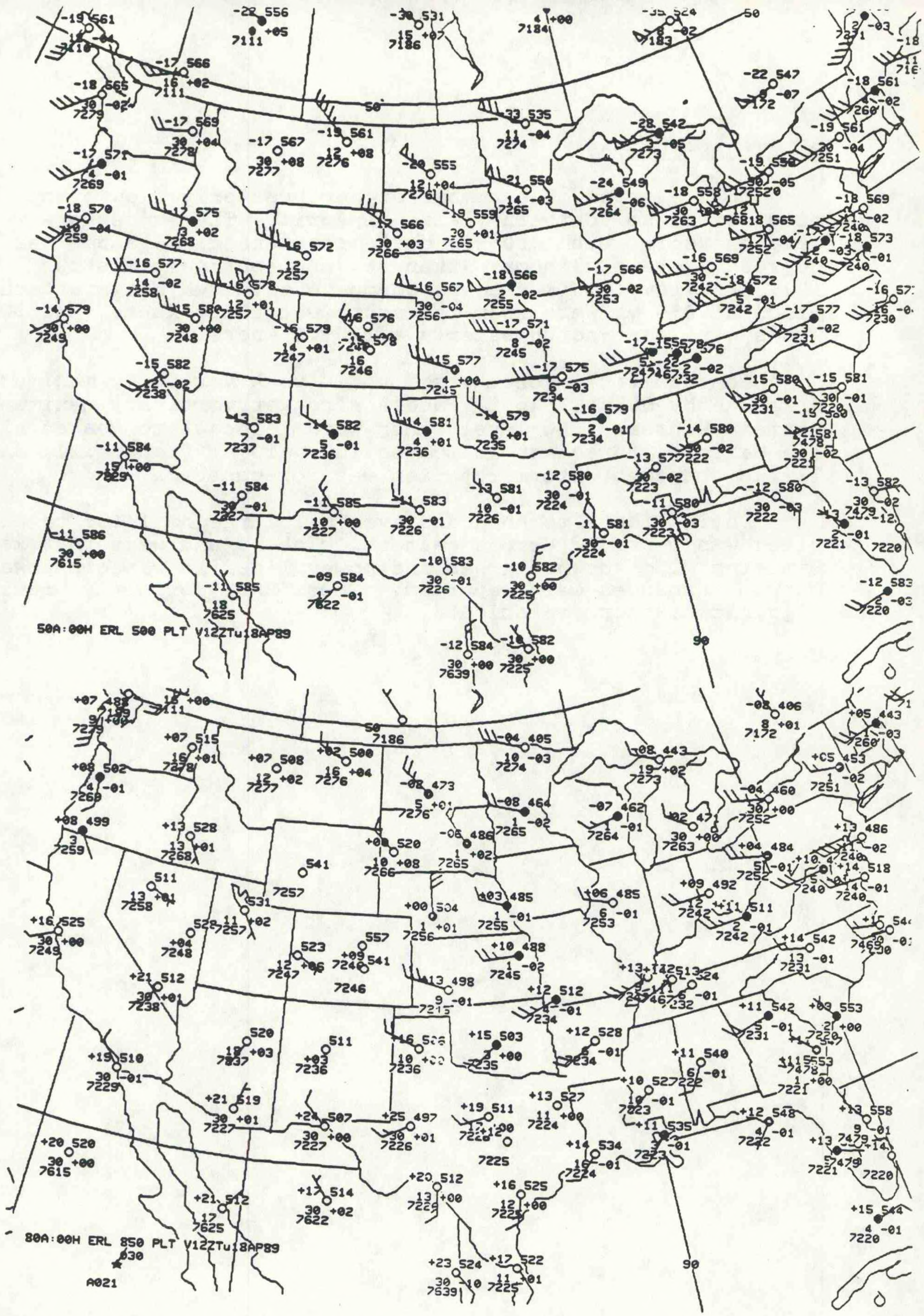


FIGURE 10: As in figure 7, but for 12Z, 18 April 1989.

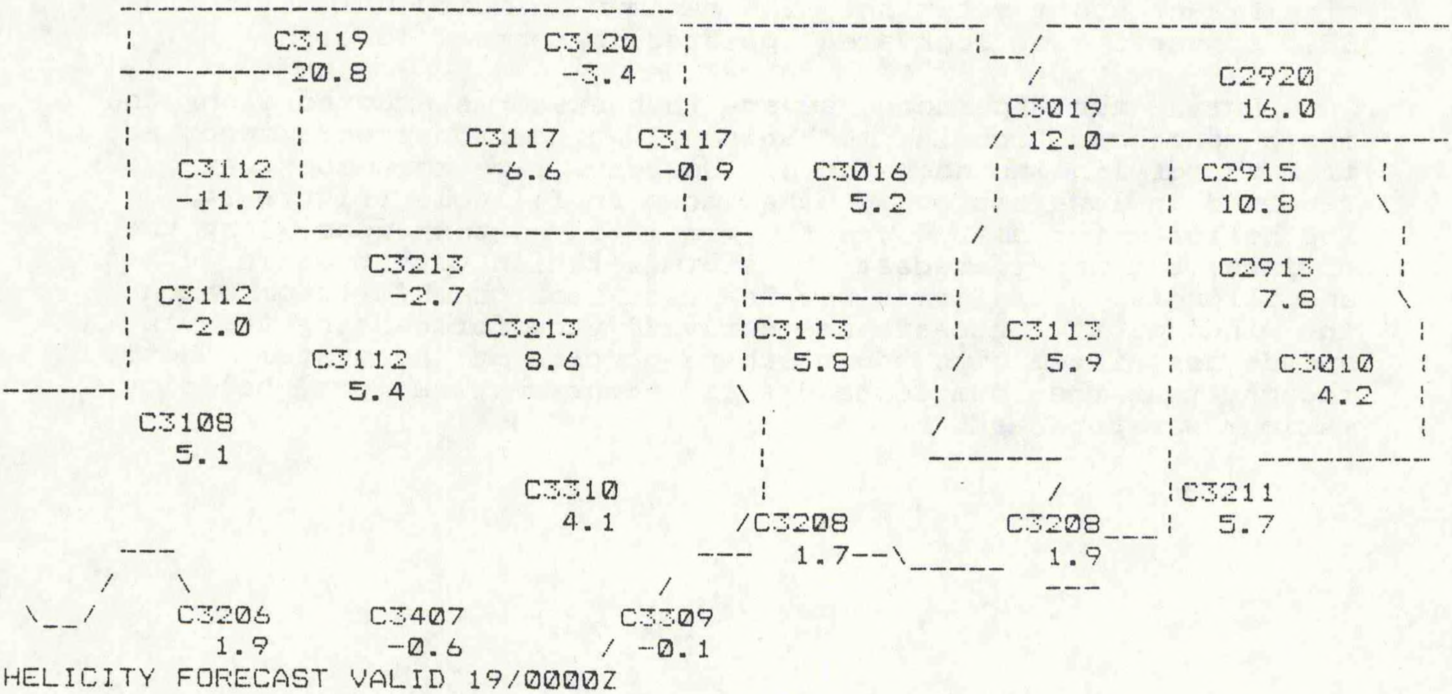


FIGURE 11: As in figure 8, but for 00Z, 19 April 1989.

4. 26 APRIL 1989

This was the second in a series of active severe weather days across the Great Plains. A large 500 mb low was centered over western Arizona (see figure 12), with southwesterly flow of 20-40 knots across most of the Plains states. South-southwesterly flow was present at 850 mb, with an 850 mb low center in western South Dakota. A stationary front across Illinois and Iowa, and a dryline extending from Kansas into west Texas, were the focusing mechanisms for the afternoon convection.

Despite the impressive-looking system over the western U.S., the helicity forecasts (figure 13) did not indicate any areas of significant storm rotation. The maximum helicity values in the SELS convective outlook area appeared in central Iowa.

During the afternoon, severe thunderstorms erupted along the above-mentioned focusing mechanisms. No tornadoes were reported from the dryline thunderstorms. However, five tornadoes were reported in Iowa and one touched down in Illinois (figure 14). The helicity forecast correctly predicted no tornadoes along the dryline, but underforecast the storm rotation potential in Iowa and Illinois. This error was the result of the LFM (from which the winds aloft forecasts are derived) underforecasting the wind speeds associated with the northern portion of the system. Note, though, that the Iowa tornadoes <u>did</u> occur where a <u>local</u> helicity maximum was forecast.

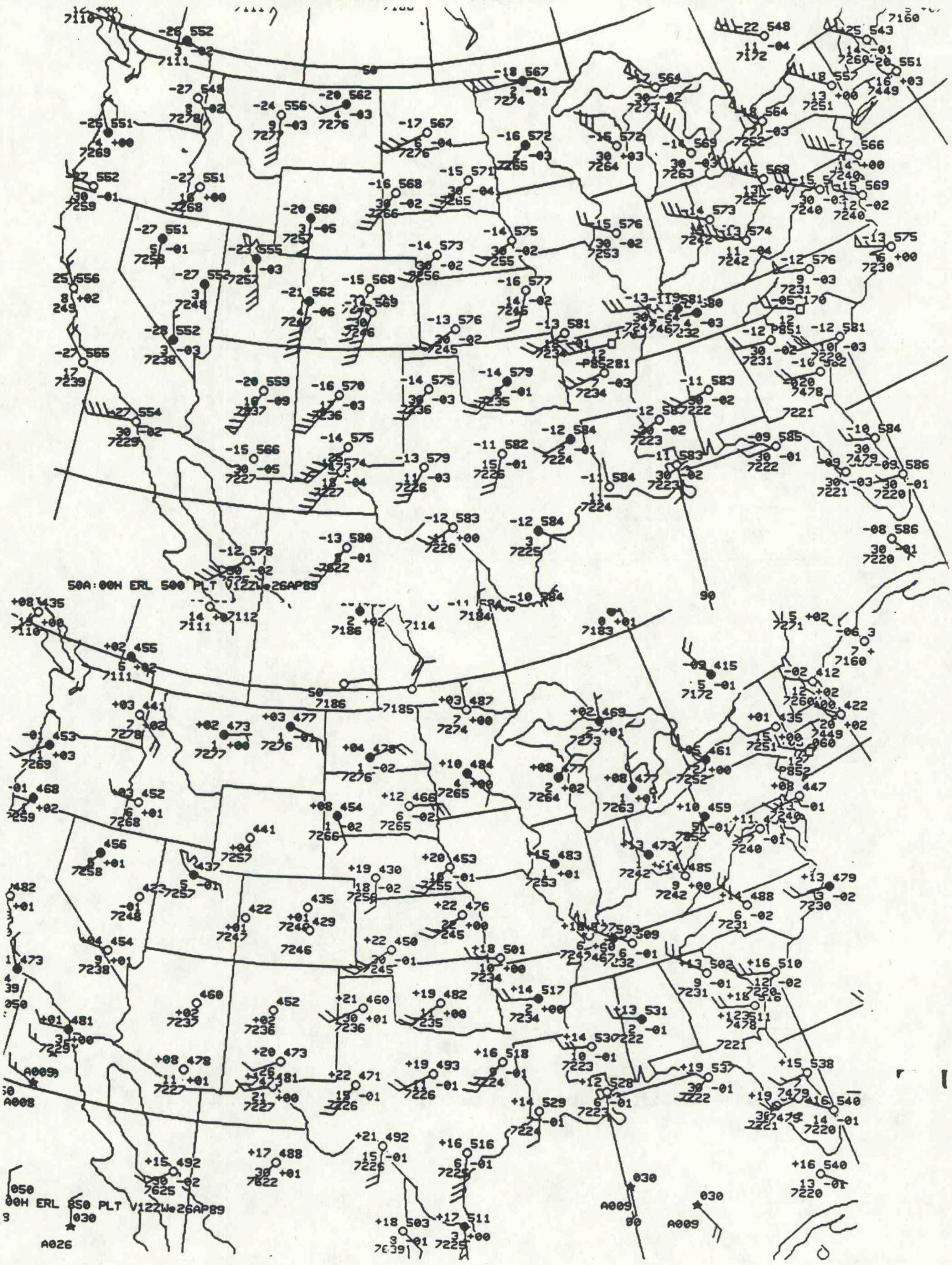


FIGURE 12: As in figure 7, but for 12Z, 26 April 1989.

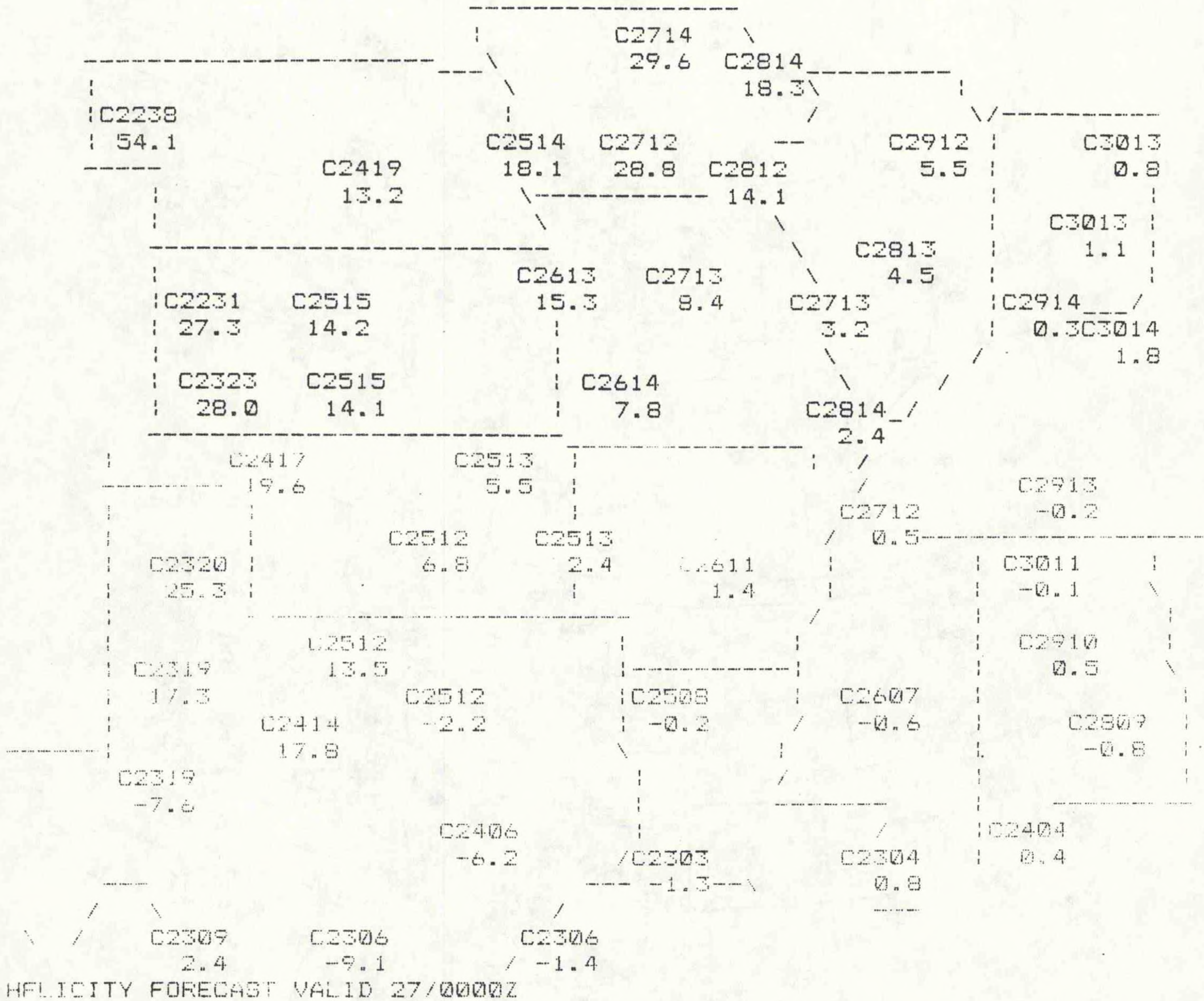


FIGURE 13: As in figure 8, but for 00Z, 27 April 1989.

FIGURE 14: As in figure 9, but for afternoon and evening of 26 April 1989.

5. 4 MAY 1989

The event in Texas on this day demonstrated the usefulness of HAFP-1, the local helicity analysis. A pronounced convergence zone at 850 mb extended along the Red River to a low in northwest Texas. The moisture axis at 850 mb extended from central Texas into the Texas Panhandle (figure 15). The flow at 500 mb was from the west-northwest at roughly 40 knots. The airmass was again quite unstable, with 850-500 mb temperature differences of 30 degrees C.

The numerical forecasts indicated strong PVA moving across the Red River by 00Z, 5 May, but weak, disorganized flow at 850 mb. The helicity forecast (figure 16) showed a weak maximum across central Texas, but the values were below the threshold to expect significant rotation.

Late in the afternoon, a derecho (Johns and Hirt, 1983) developed in the southern Panhandle of Texas. The derecho surged southeastward at speeds of up to 60 knots. Numerous reports of tornadoes and extreme downburst winds were received along the derecho's path.

The HAFP-1 analysis from the 00Z Stephenville sounding (figure 17) shows that the 12-hour HAFP-2 forecast verified fairly well with respect to the empirically-predicted storm motion and helicity along the predicted storm motion. However, when the actual cell motion of the derecho (roughly 310 degrees at 50 knots) is used rather than the empirically-predicted cell motion, the storm-relative helicity increases dramatically. It can be said that the derecho's extremely deviant cell motion was responsible for tornado development in an environment which otherwise would probably have not supported storm rotation.

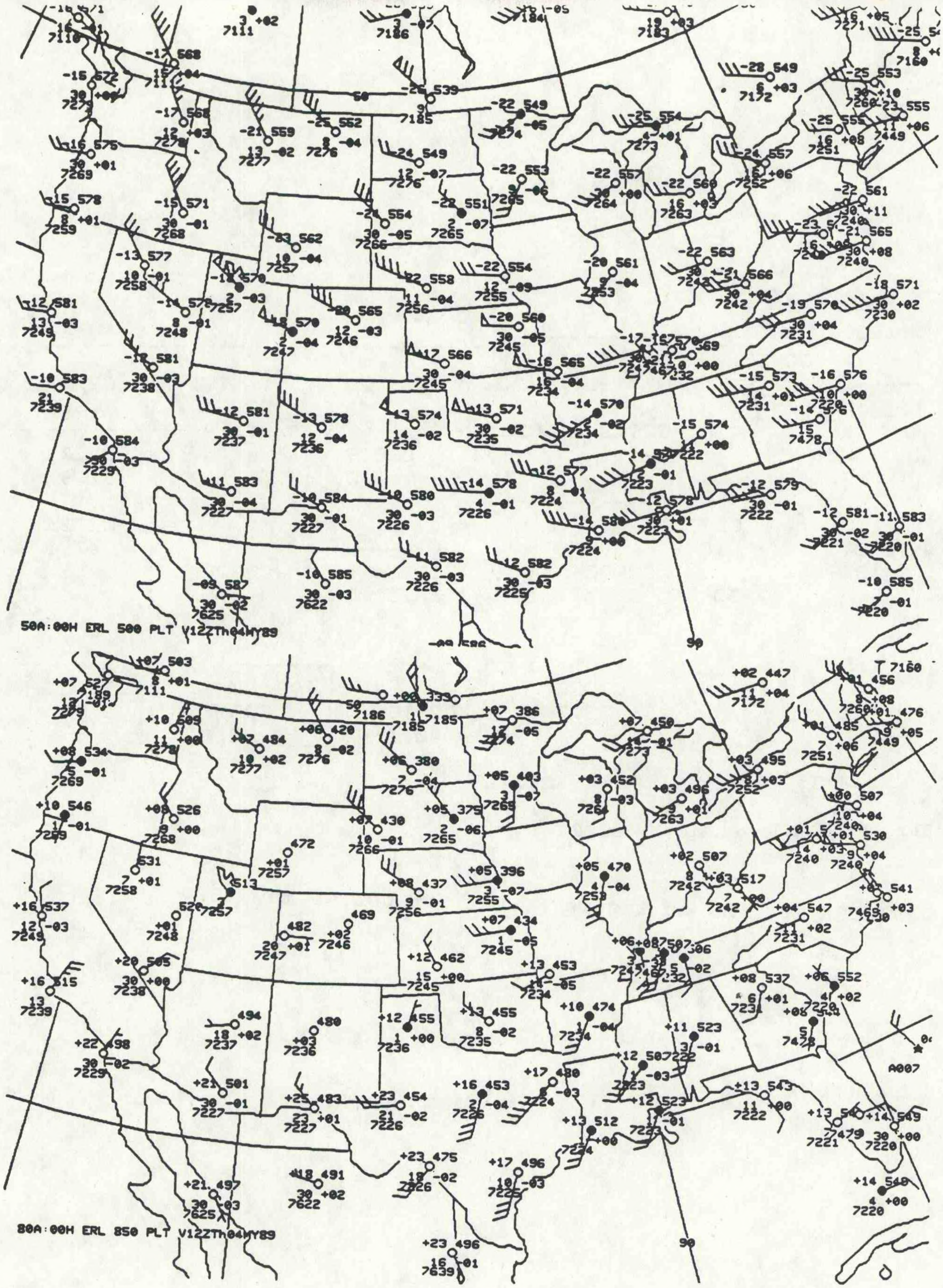
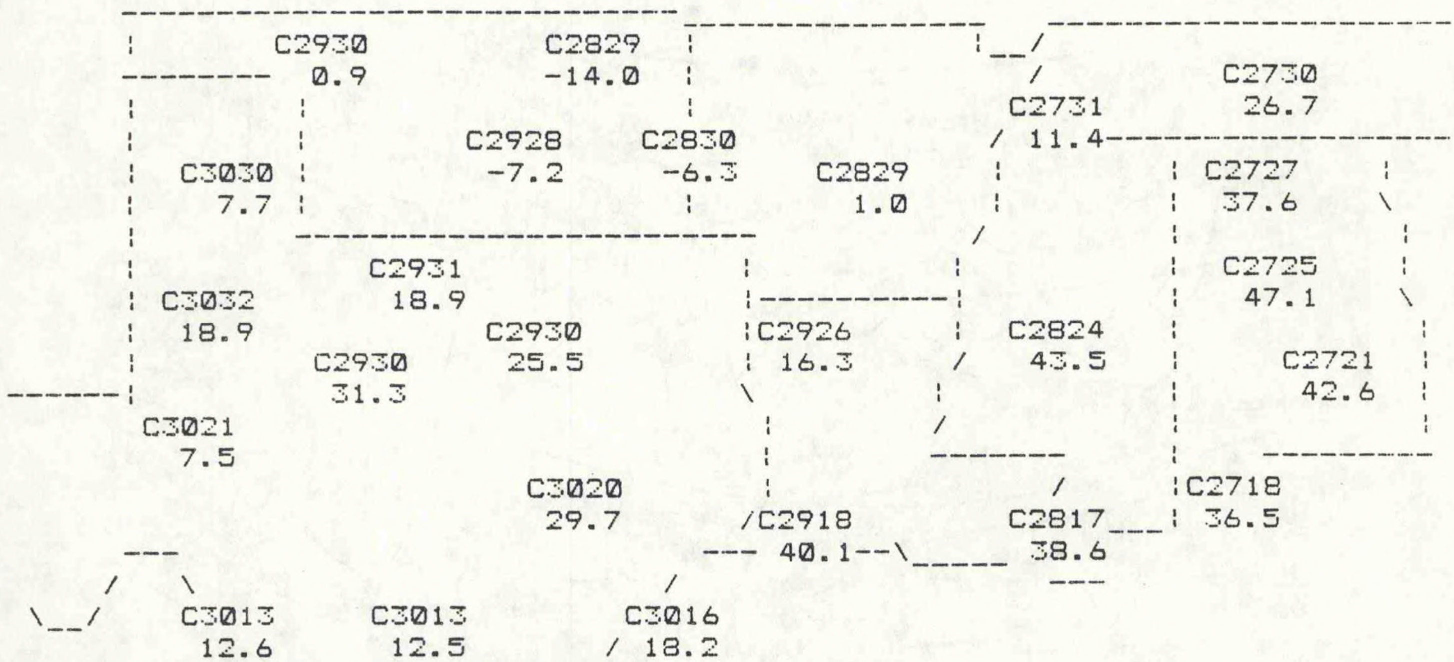


FIGURE 15: As in figure 7, but for 12Z, 4 May 1989.



HELICITY FORECAST VALID 05/0000Z

FIGURE 16: As in figure 8, but for 00Z, 5 May 1989.

NNNNHELICITY ANALYSIS FOR STATION SEP
USING DATA FROM 05/0002Z

MEAN WIND AZIMUTH = 280.1 DEGREES
MEAN WIND SPEED = 38.1 KNOTS

PREDICTED SEVERE STORM MOTION AZIMUTH = 294.9 DEG
PREDICTED SEVERE STORM MOTION VELOCITY = 26.7 KTS

MEAN ENVIRONMENTAL HELICITY FOR SURFACE-4 KM LAYER

CELL MOVEMENT SPEED IN KNOTS

AZ	10	20	30	40	50
260	12.0	-1.0	-13.9	-26.9	-39.9
270	15.9	6.8	-2.3	-11.4	-20.5
280	20.0	15.1	10.1	5.2	0.2
290	24.3	23.7	23.0	22.4	21.7
300	28.7	32.3	36.0	39.7	43.3
310	32.9	40.7	48.6	56.5	64.4

FIGURE 17: HAFP-1 analysis for Stephenville TX, 0002Z, 5 May 1989.

6. 8 MAY 1989

Northwesterly flow was present at 500 mb on May 9. At 00Z, 9 May 1989 (12Z analyses from 8 May were not available due to local AFOS problems), wind speeds at 500 mb were around 40 knots, with a speed maximum moving through northwest Arkansas and southwest Missouri. At 850 mb, southwesterly flow (up to 30 knots) ahead of a low in northwest Texas pushed the moist axis into southwest Missouri, central Oklahoma, and east Texas (figure 18).

The progs called for a small vorticity maximum to track to southern Missouri by 00Z, 9 May. The 850 mb flow was to remain fairly strong from the southwest across the South Central States. The helicity forecast (figure 19) indicated a potential for storm rotation from north Texas to Western Tennessee. Combined with the SELS outlook, the tornado outlook area (figure 20) extended from northwest Texas to western Mississippi, with a 66.1 maximum over northeast Texas suggesting the potential for enhanced tornado production in this area.

Severe thunderstorms produced tornadoes in extreme eastern Oklahoma, extreme eastern Arkansas, and extreme northwest Mississippi (figure 20). The storms did not produce as many tornadoes as expected from the forecast, but all of the tornadoes occurred within the tornado outlook area.

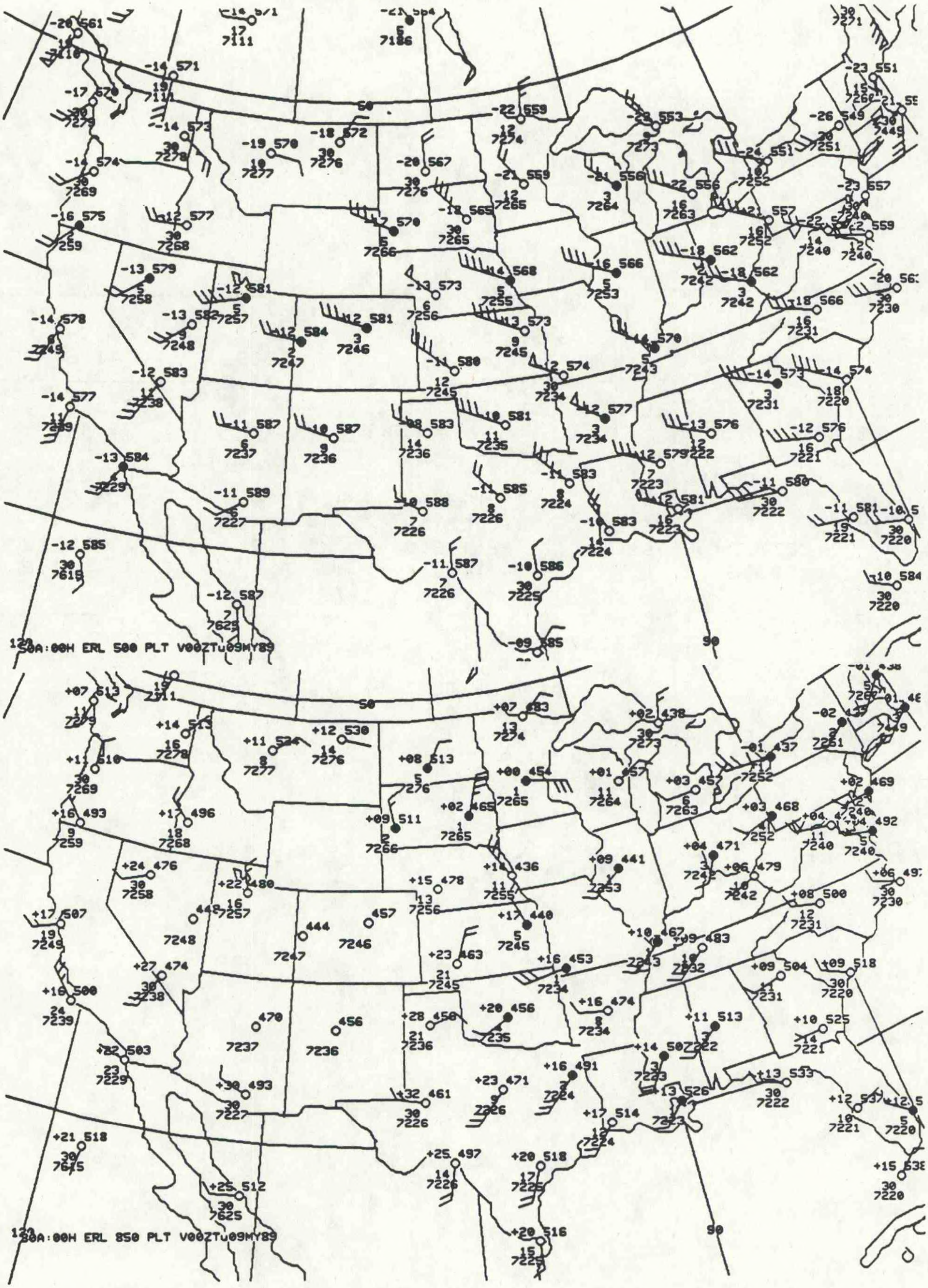


FIGURE 18: As in figure 7, but for 00Z, 9 May 1989.

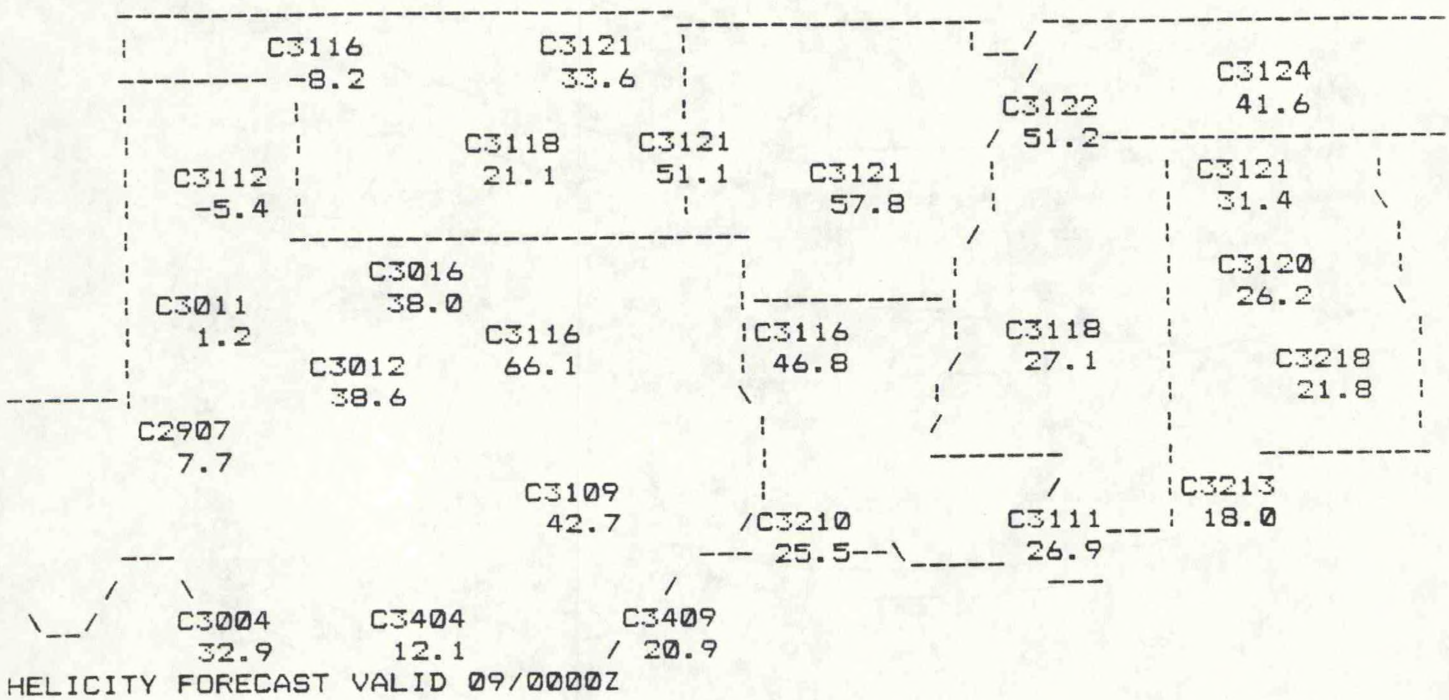


FIGURE 19: As in figure 8, but for 00Z, 9 May 1989.

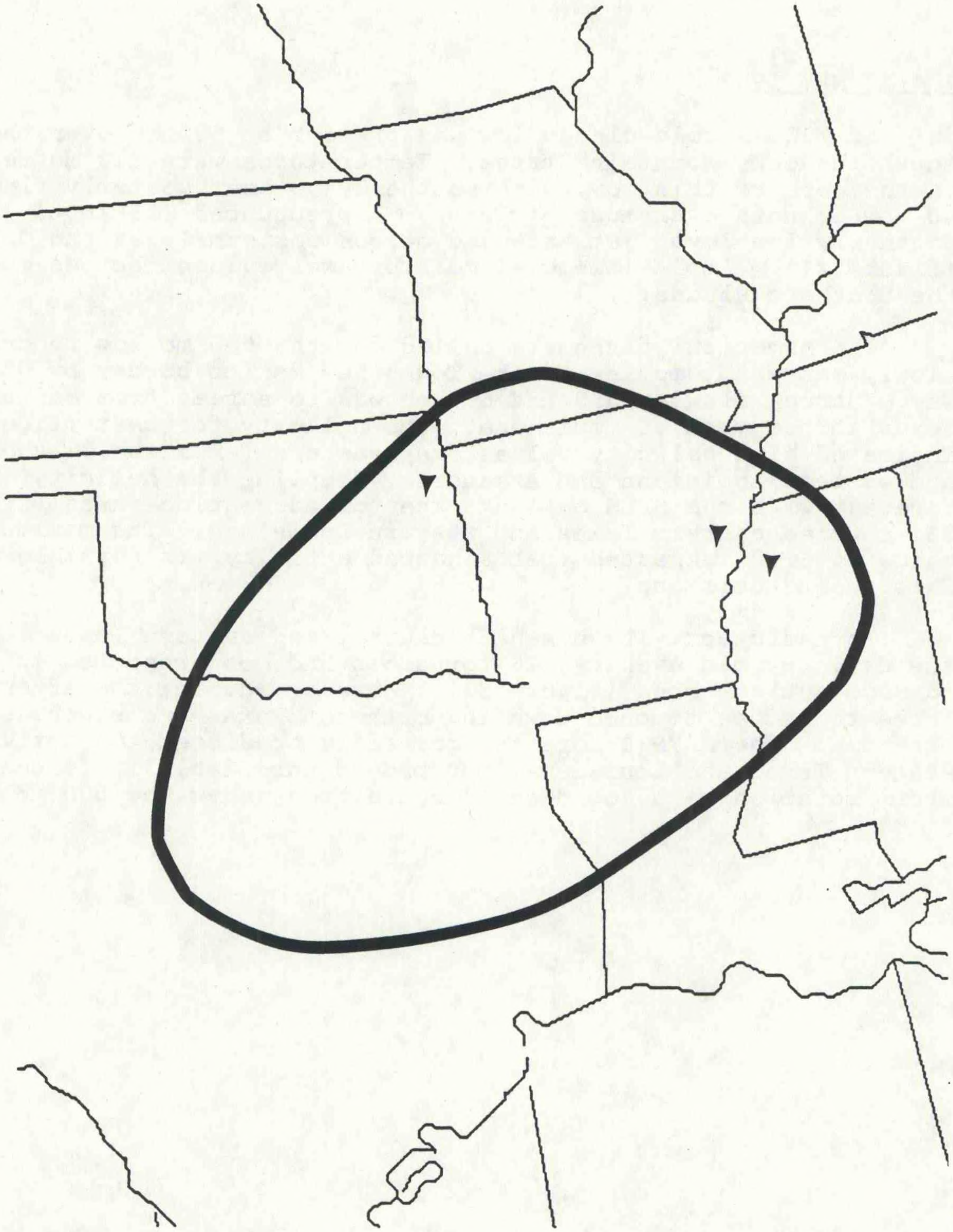


FIGURE 20: As in figure 9, but for afternoon and evening of 8 May 1989.

7. 17 MAY 1989

At 12Z, a cold closed low was present at 500 mb over the southern Rocky Mountain States. Temperatures were -18 degrees C in the core of this low, with southerly to southwesterly flow of 40 to 65 knots over most of Texas. A pronounced (55 knot) southerly low-level jet extended across eastern Texas and Oklahoma (figure 21). Ample low-level moisture was evident across much of the Southern Plains.

The numerical forecasts called for the 500 mb low to drift slowly eastward, moving to the Texas-New Mexico border by 00Z, 18 May. Strong flow at 850 and 500 mb was to spread from eastern Texas across much of Louisiana. The helicity forecast (figure 22) indicated high helicity values over eastern Texas and Oklahoma, and western Louisiana and Arkansas. Coupling the helicity forecast with the SELS outlook, the tornado outlook area (figure 23) covered eastern Texas and western Louisiana. The maximum value of 61.0 suggested that enhanced activity was possible near Shreveport Louisiana.

Tornadic activity began in central and eastern Texas early in the day. By mid-evening, 23 tornadoes had been reported in the tornado outlook area (figure 23). However, during the afternoon, three tornadoes touched down in northwest Texas and southwest Oklahoma. The HAFP-2 forecast correctly predicted the activity in eastern Texas and Louisiana, but proved unreliable in forecasting storm rotation with "cold pool" convection under the 500 mb low.

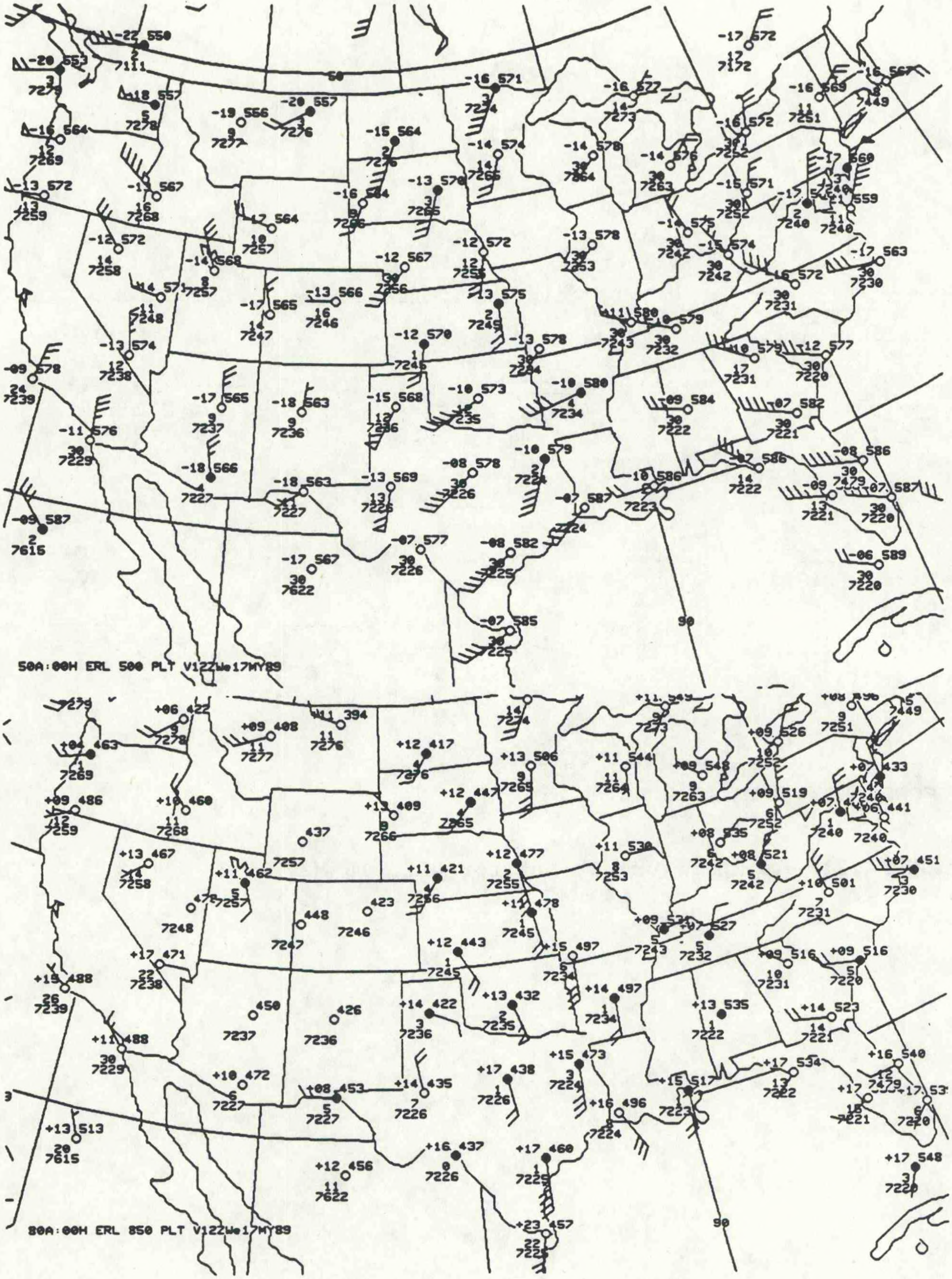


FIGURE 21: As in figure 7, but for 12Z, 17 May 1989.

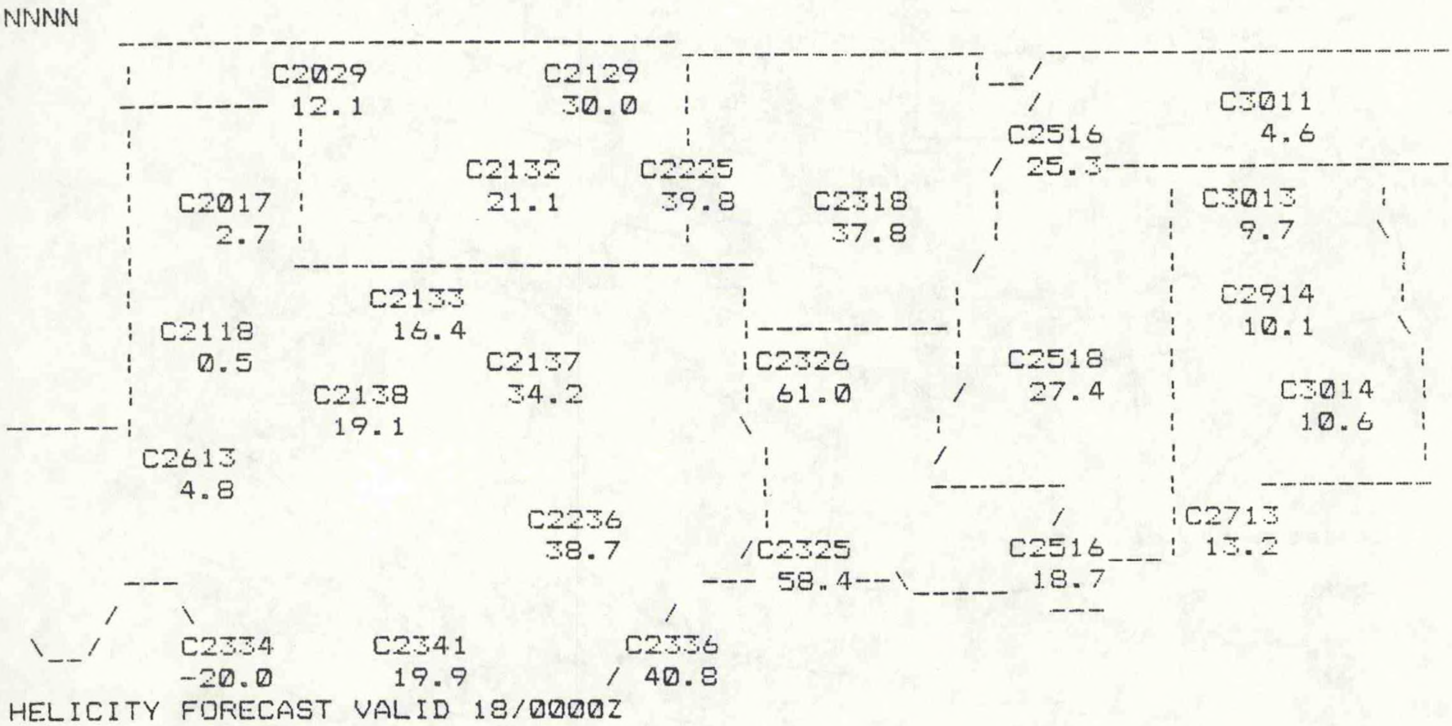


FIGURE 22: As in figure 8, but for 00Z, 18 May 1989.

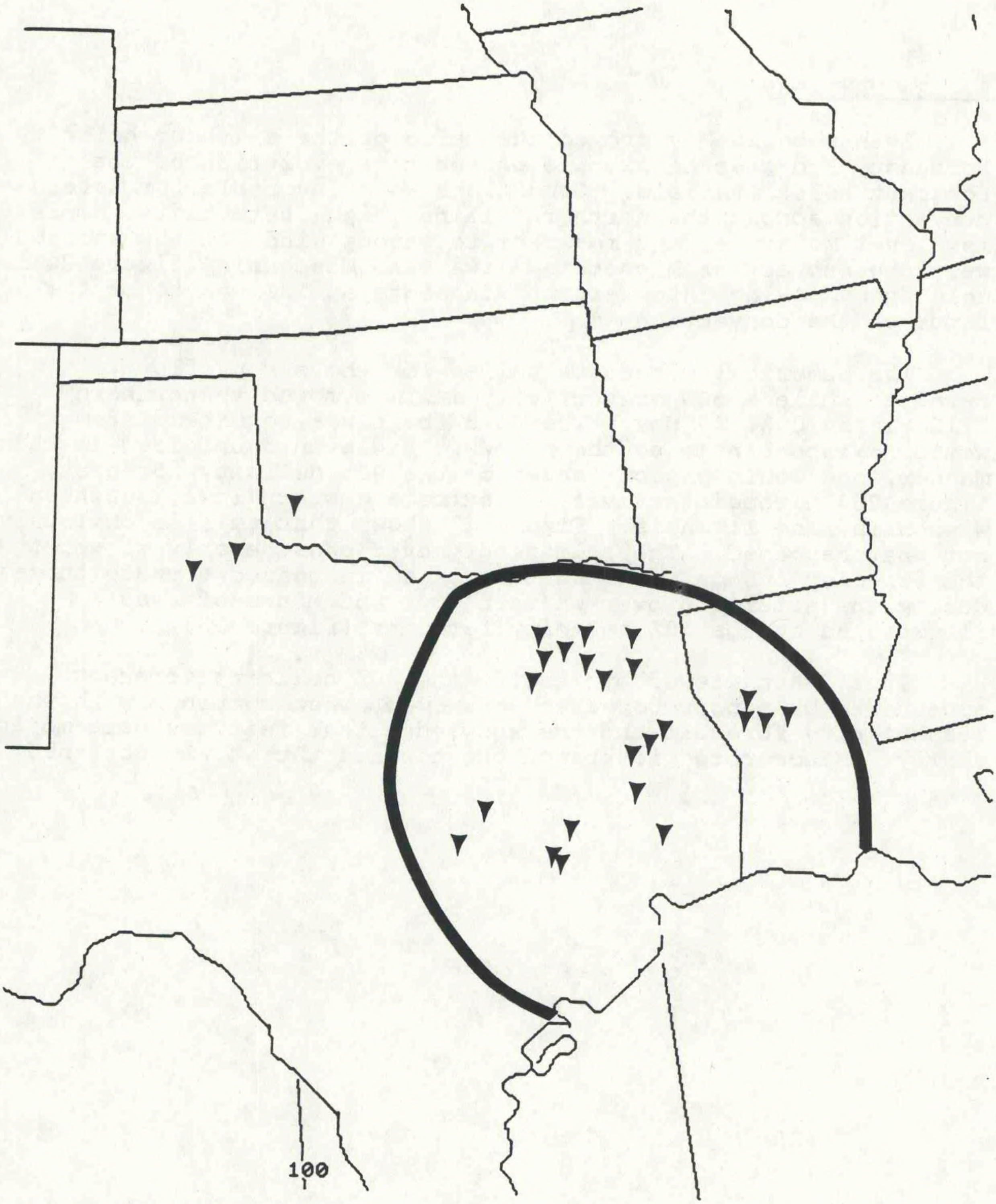


FIGURE 23: As in figure 9, but for afternoon and evening of 17 May 1989.

8. 24 MAY 1989

Events on 24 May proved the value of the six-hour helicity forecast, and gave an example of the time evolution of the forecast helicity field. Conditions were favorable for severe convection across the northern Plains; high instability, ample low-level moisture, and moderate to strong winds at 850 and 500 mb were present across Minnesota, Iowa, and Wisconsin (figure 24). A cold front moving into western Minnesota at 12Z was to be the focus of the convection.

The numerical forecasts called for the strong flow to persist, while a 500 mb vorticity maximum moved to northern Illinois by 00Z, 25 May. The cold front was to extend from western Wisconsin to southern Iowa. Had events unfolded in this manner, one would expect (based on the 00Z helicity forecast, figure 26) tornadic activity in extreme eastern Iowa, southern Wisconsin, and Illinois. Figure 27 shows that this is obviously not what happened. The cold front moved considerably slower than the forecast indicated, resulting in an increased tornado threat during the afternoon over western Iowa and Minnesota, as illustrated by the 18Z helicity forecast (figure 25).

Thus, when viewed by itself, the 00Z helicity forecast appears to be a poor forecast. However, when combined with the 18Z helicity forecast and the knowledge that features were moving slowly, an accurate picture of the tornado threat was obtained.

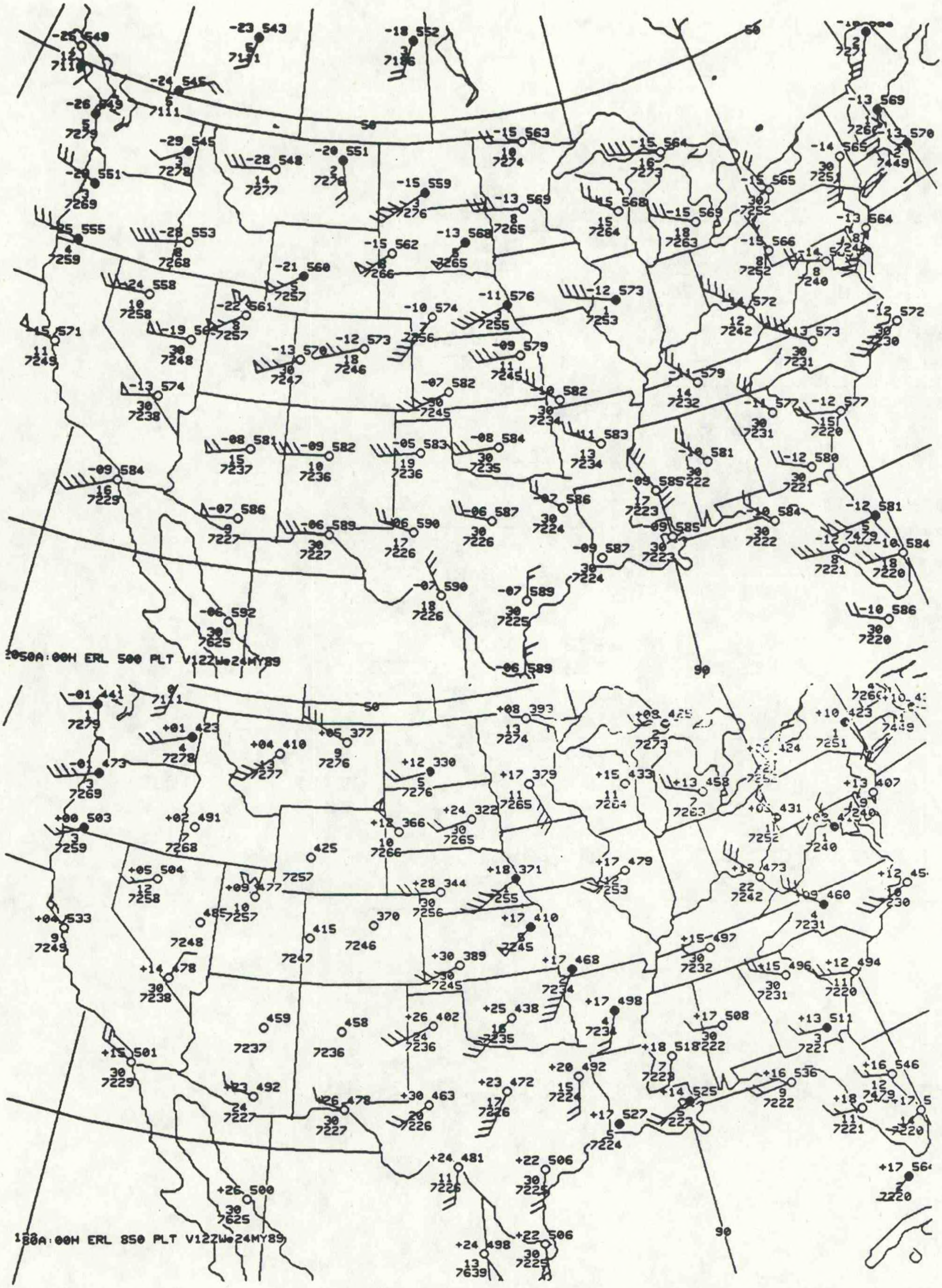
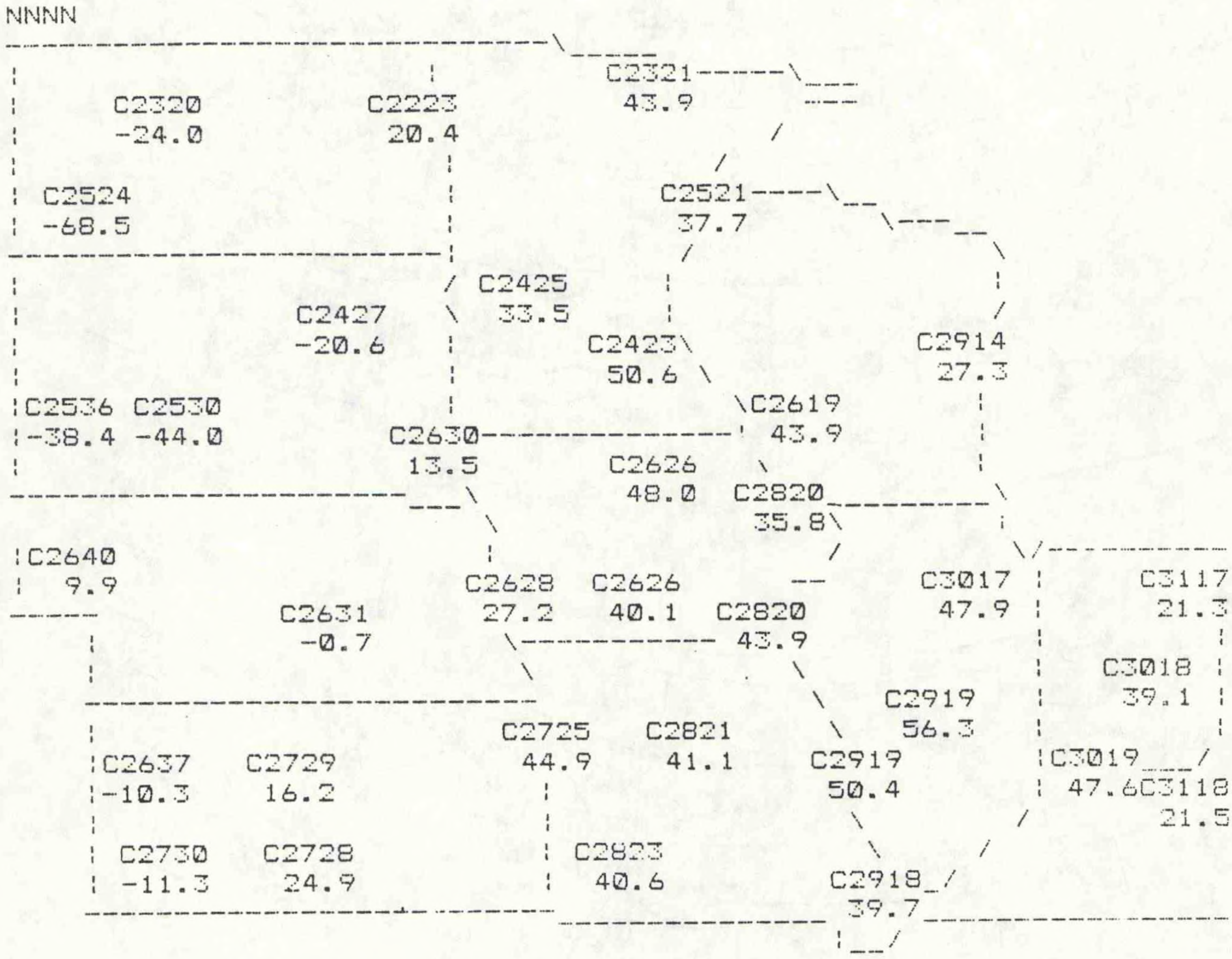
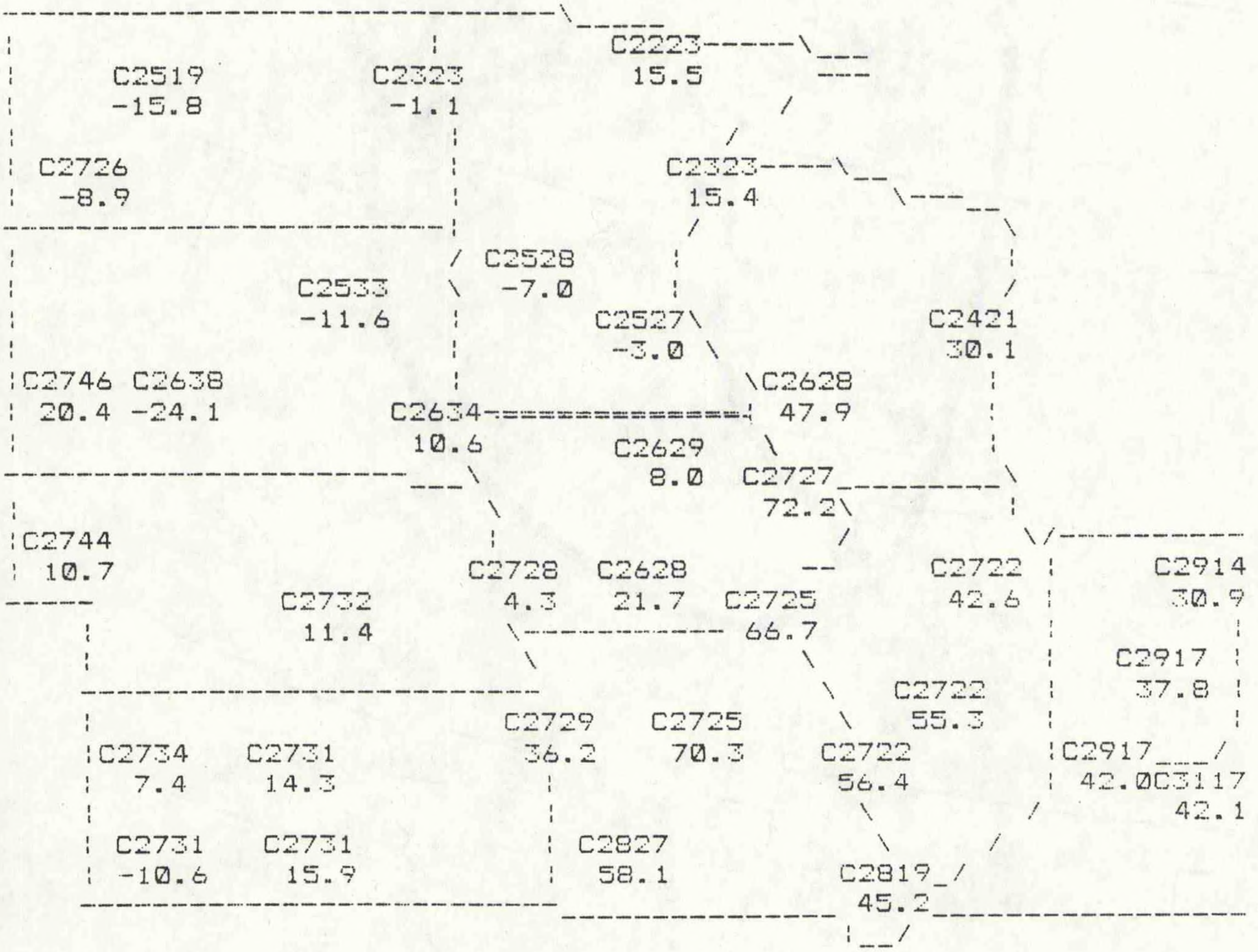


FIGURE 24: As in figure 7, but for 12Z, 24 May 1989.



HELICITY FORECAST VALID 24/1800Z

FIGURE 25: As in figure 8, but for 18Z, 24 May 1989.



HELICITY FORECAST VALID 25/0000Z

FIGURE 26: As in figure 8, but for 00Z, 25 May 1989.

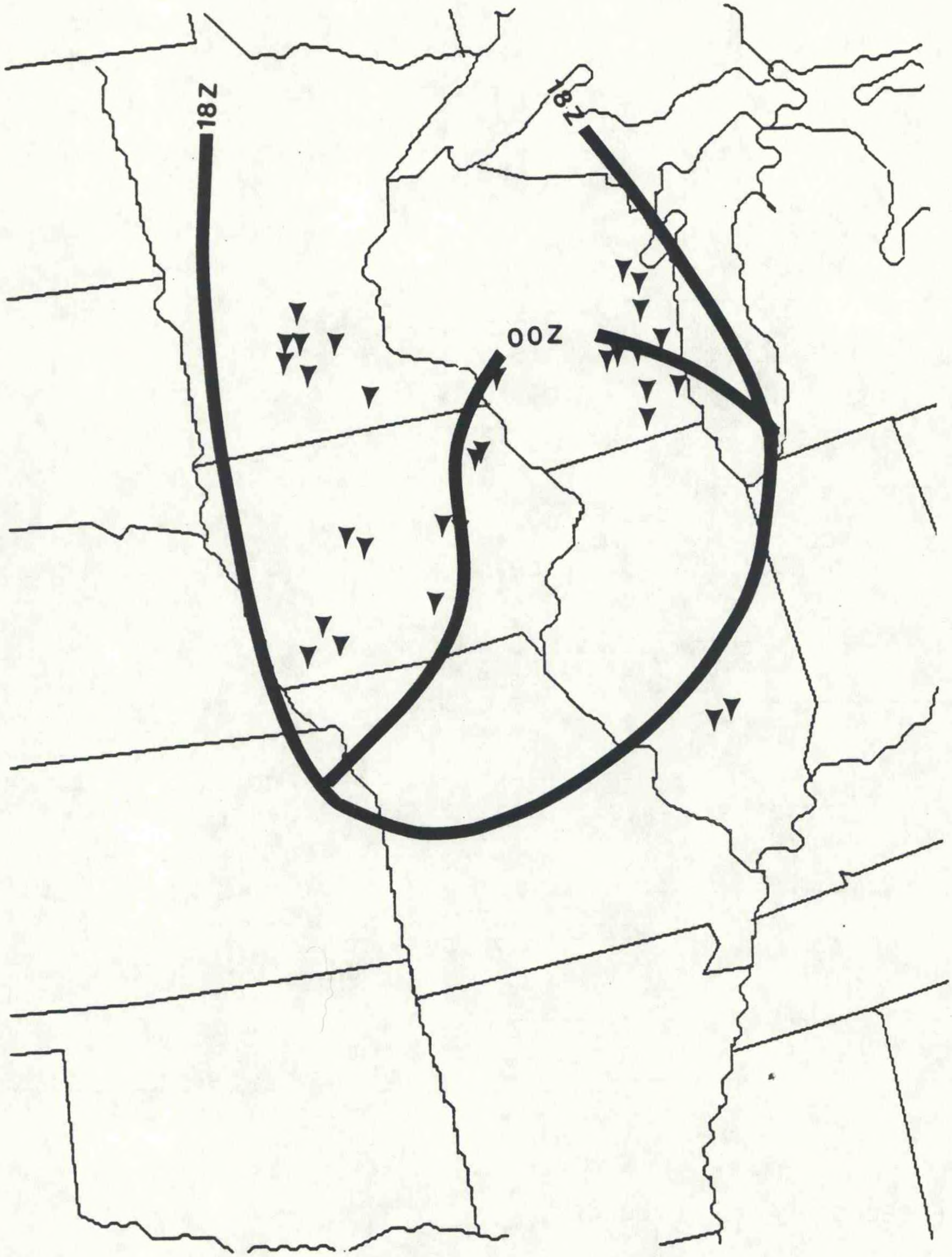


FIGURE 27: As in figure 9, but for afternoon and evening of 24 May 1989

9. 11 JUNE 1989

At 12Z, a convectively-induced vorticity maximum at 500 mb was moving eastward across Oklahoma. Moderate 500 mb flow of 30-40 knots was present across most of the Southern Plains and South Central States. A 30 knot southerly low-level jet and ample moisture were evident across this region at 850 mb (figure 28).

The numerical progs for 00Z, 12 June increased the 850 mb flow across the South Central States. A broad trough axis at 500 mb was to move into eastern Texas and eastern Oklahoma. The 00Z helicity forecast indicated a small area of high helicity from northern Arkansas into extreme western Kentucky (figure 29). The marginal helicity values in the tornado outlook area (figure 30) suggested that only a few tornadoes might form in this area.

During the afternoon and evening, five tornadoes were reported (figure 30). One "maverick" tornado (well away from the tornado outlook area) occurred in the Texas Panhandle, but the remaining four touched down within the tornado outlook area. This was a good example of HAFP-2 pinpointing a small area of potential storm rotation.

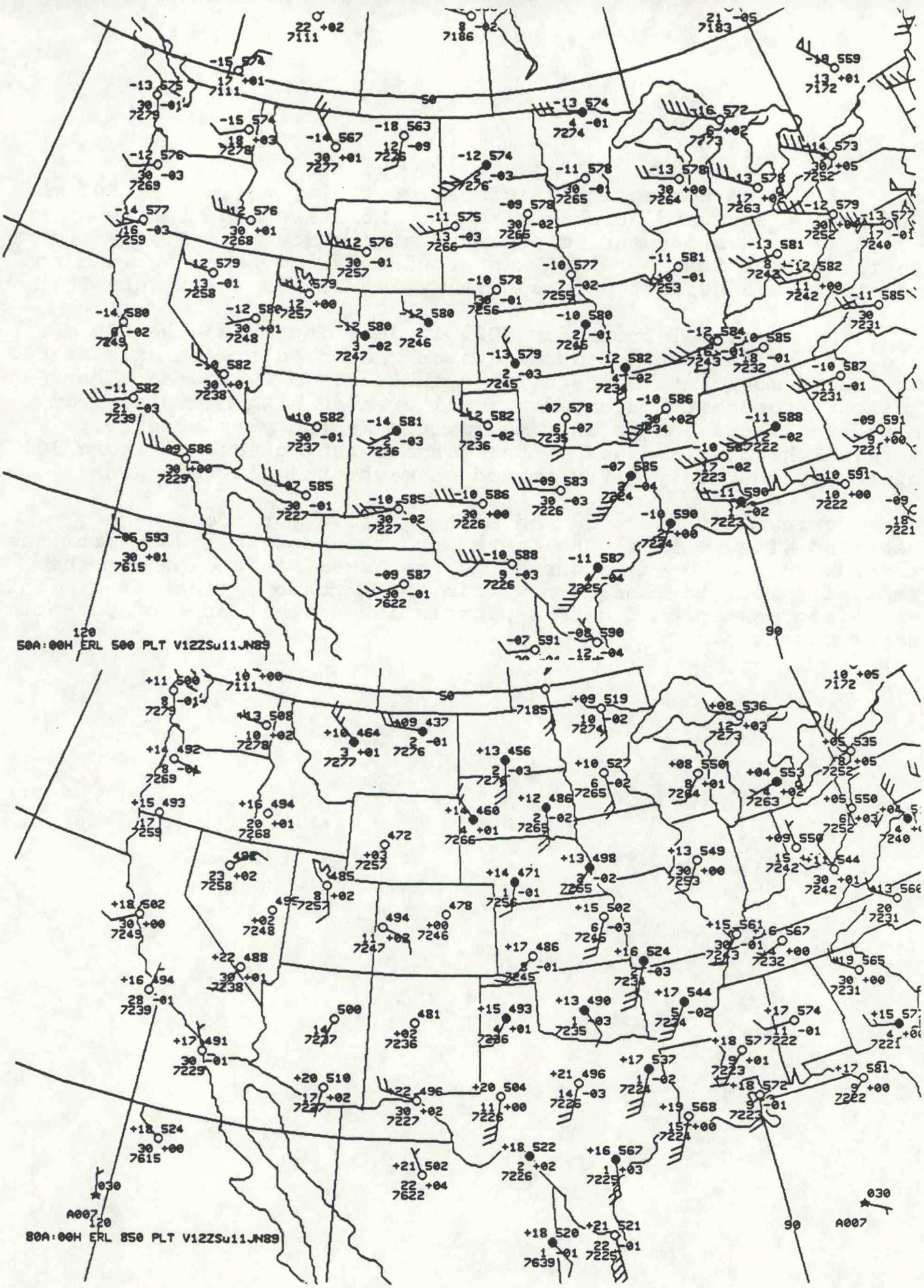


FIGURE 28: As in figure 7, but for 12Z, 11 June 1989.

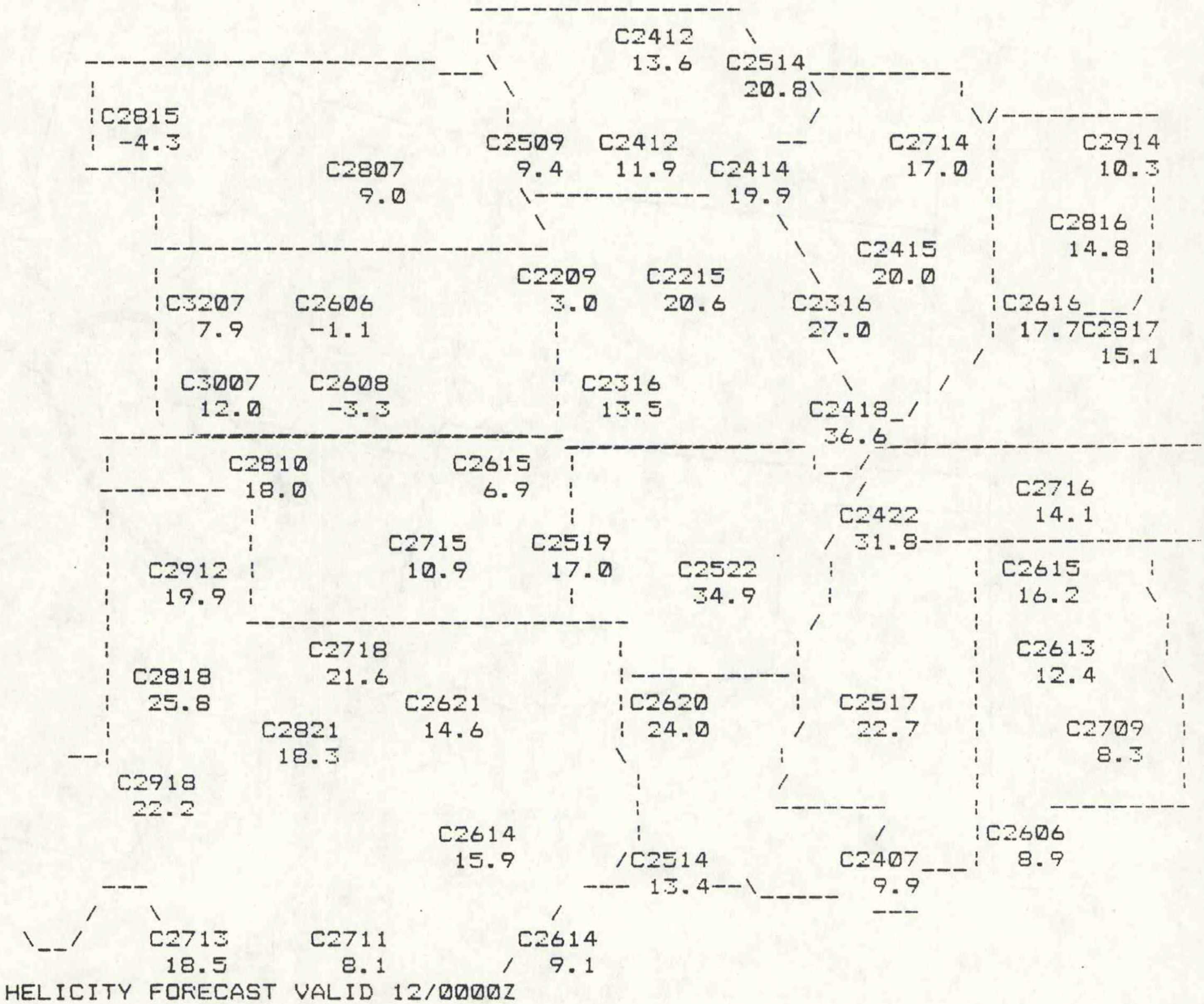


FIGURE 29: As in figure 8, but for 00Z, 12 June 1989.

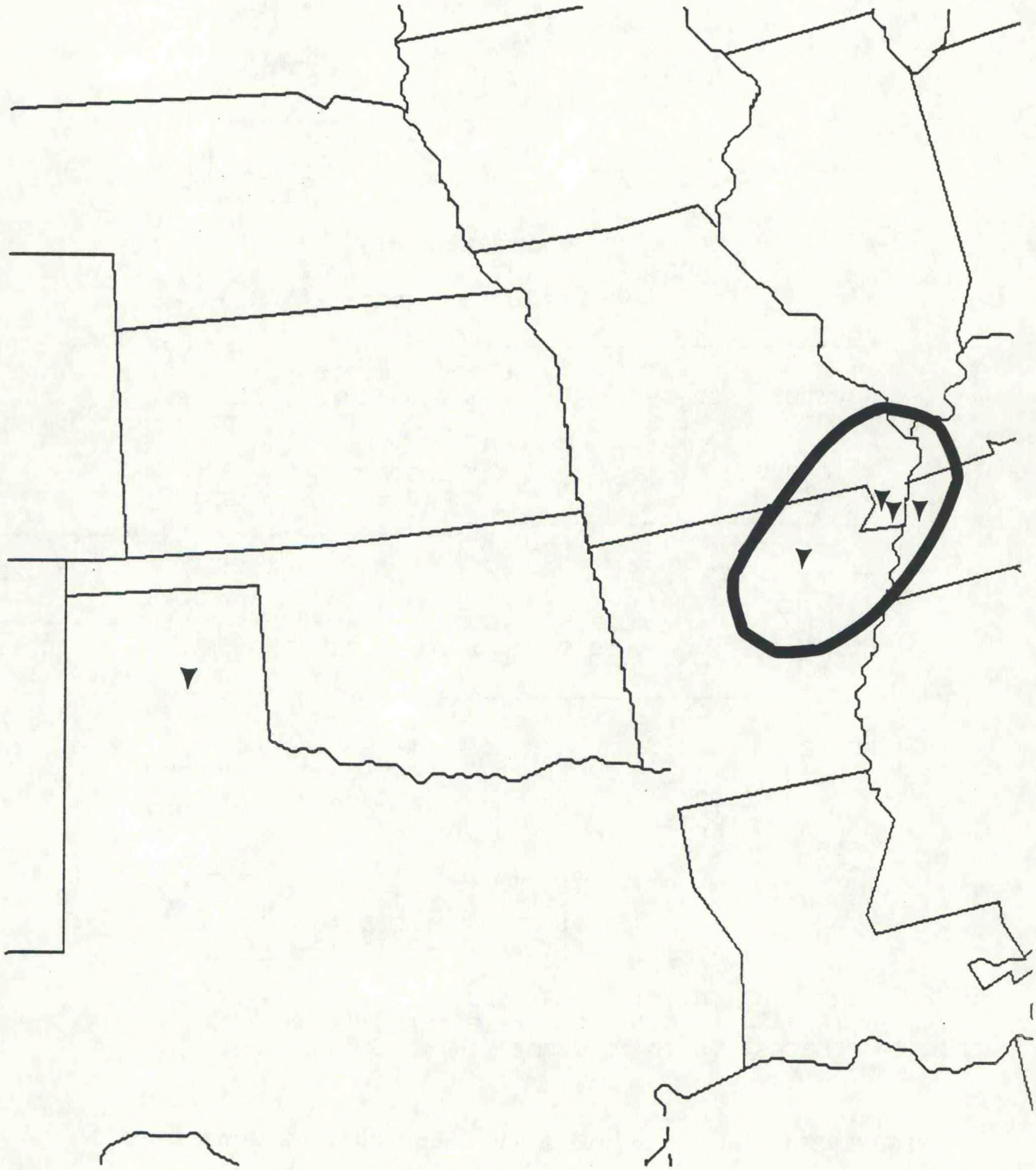


FIGURE 30: As in figure 9, but for afternoon and evening of 11 June 1989.

10. QUANTIFICATION OF HAFP TORNADO FORECASTS

In an attempt to qualitatively predict the amount of tornado activity near a forecast site, the results of the 19 case studies were used to derive a MOS-type guidance package. This package relates the analyzed/forecasted helicity values to the number of tornado reports within 75 miles of the forecast site.

The procedure used to derive this guidance was straightforward. First, the helicity values were divided into 10-unit increments. Second, a 75-mile radius circle was centered on each forecast site in or near a SELS severe weather outlook area. Third, the number of tornadoes within the 75-mile circle were determined and categorized as follows: none, 1-2, 3-5, 6-8, and 9 or more. Finally, the probability of each combination of helicity value and tornado coverage were converted into elements on the 2-dimensional matrix shown below.

PROBABILITY OF TORNADOES
WITHIN 75 MILES OF FORECAST SITE

FCST.	NUMBER OF TORNADOES				
HEL.	0	1-2	3-5	6-8	9+
10-20	80	10	10	0	0
20-30	70	20	10	0	0
30-40	20	20	50	10	0
40-50	10	10	60	20	0
50-60	10	20	10	50	10
60-70	10	10	20	40	20
70-80	0	10	20	30	40
80-90	0	0	20	30	50

Obviously, a table such as this will undergo evolution as subsequent years' tornado statistics are added to the record. Thus, there will be means for a centralized source (possibly regional offices) to annually update the database used to construct this table and provide new guidance each storm season for the NWS field offices.

VI. SUMMARY AND DISCUSSION

Recent research has suggested that helicity plays an important factor in the behavior of the supercell thunderstorm. Helicity, defined as the dot product of the velocity and vorticity vectors, was observed to be large in the environment of tornadic storms. Thus, if one could analyze and predict the helicity of a thunderstorm's environment, one could predict the probability and extent of tornado formation over a particular area.

HAFP-1 does a detailed analysis and/or 12-hour forecast of helicity for a single upper-air station on the ABT. HAFP-2 forecasts helicity for only the predicted severe storm motion, but gives forecasts (six, 12, or 24 hours) for the stations in a four to eight state geographical region.

HAFP-1 will be useful in "nowcasting" the cells with highest tornado potential. This in turn would allow for the strategic positioning of spotters, and possibly for earlier tornado warnings. Additionally, the 12-hour forecast would enable additional staffing requirement decisions to be made early in the day, hopefully well before thunderstorms broke out.

HAFP-2 would, along with programs such as ADAP, indicate areas of highest tornado potential well before such activity occured. This could enable forecasters at SELS to issue watch boxes earlier and with greater confidence, and provide another tool for differentiating between severe thunderstorm and tornado environments.

The programs described here performed remarkably well. In the controlled preliminary verification studies, helicity values were favorably associated with the observed extent of tornadic activity. In the case studies, the program accurately predicted the vast majority of tornadoes, while maintaining a relatively low false alarm ratio.

Perhaps more important than HAFP's successes were the times it was not reliable. Listed below are some rules of thumb developed from the case studies:

1) HAFP will tend to overestimate the tornado potential when the convection is high-based. This was observed on 20 April, and is believed to be the cause of the excessively high forecasts on 2 May and 8 May (see table on page 22).

2) HAFP is essentially an LFM-based product. Any errors in forecasting made by the LFM will show up in the winds aloft forecasts, and in turn will show up in the helicity forecasts. Satellite data and NMC discussions can be used to qualitatively adjust the helicity forecast as was done on 24 May.

3) The local analysis (HAFP-1) serves as a good backup if

cell motion deviates from the predicted cell motion, as was the case on 4 May. This was also observed with an Arkansas supercell on 15 November.

The most exciting aspect of HAFP is the promise it holds for the future, when data in greater temporal and spatial resolution will be available. As the reorganization of the National Weather Service takes place, and the NEXRAD and wind profiler networks are installed, it will be possible to operationally observe near-mesoscale phenomena. Combining the winds-aloft data from NEXRAD or profilers with surface observations and a HAFP algorithm, hourly helicity analyses could be generated. Locally-available products such as this will be especially important if the WFO's become responsible for the issuance of severe weather watches for their forecast areas.

ACKNOWLEDGEMENTS

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