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# OBSERVATIONS OF SEVERE STORMS ON 26 AND 28 APRIL 1971

Charles L. Vlcek

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National Severe Storms Laboratory
Norman, Oklahoma
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## FOREWORD

The National Severe Storms Forecast Center, the National Severe Storms Laboratory, and the National Weather Service Forecast Office at Oklahoma City are cooperating in search of improved methods for severe storm prediction and warning. This paper by Mr. Vlcek discusses observations of two storm complexes in Oklahoma. One was marked by accurate predictions and timely warnings to affected communities; the other found the public with poor predictions and little or no warnings.

These studies illustrate the materials ideally available to today's practicing forecaster from contour mapping radar, surface stations, and upper air sounding equipment. Although our basic knowledge and observing and communicating systems do not yet provide the capability needed for forecasts and warnings of uniformly high accuracy and desired timeliness, the principal lesson of this study is that improved service should result when several indicators are available. For example, a radar indication that a thunderstorm is approaching severe proportions should be carefully regarded, even when severe storminess has not been foreshadowed in storm watches.

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OBSERVATIONS OF SEVERE STORMS
ON 26 AND 28 APRIL 1971

Charles L. Vlcek

Case histories of two severe thunderstorm situations in Oklahoma illustrate how the WSR-57 contour display aids identification of severe local storms. The path leading from analysis of the radar display and other data to dissemination of severe storm advisories is examined. Results indicate present and potential roles of various information sources in the weather warning system.

## CASE 1 - 26 APRIL 1971

A strong hint of severe weather was indicated by the middle and upper air charts for 0600 CST 26 April 1971. A deep trough at 500 mb was centered over the southern Nevada-Utah border with height falls and cold advection over a large region west of Oklahoma. The trough was quite marked at 700 mb also, and the regions of cold advection were again just west of Oklahoma. At 850 mb, a warm tongue lay over central Oklahoma while cold air was pouring into the Texas panhandle. Winds were not particularly strong, though significant differences prevailed in the reported wind direction at 850 mb (270/30 at Amarillo, 290/30 at Abilene, 210/30 at Altus), indicative of the large surface low pressure area centered over western Oklahoma. A strong cold front was entering Oklahoma from the northwest while a dry line approached from the west (fig. 1).

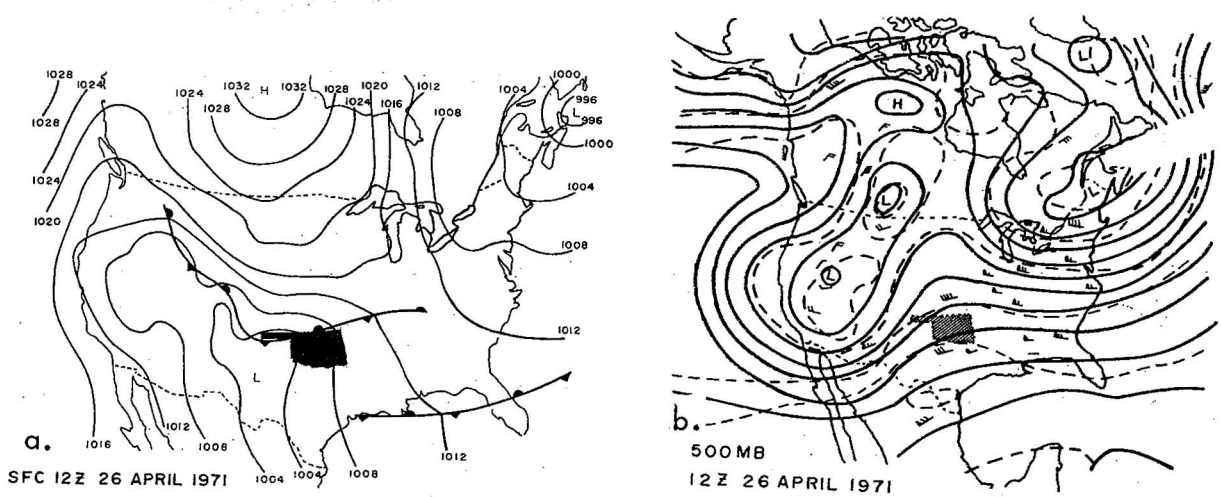



Figure 1. Analysis maps for 26 April 1971 at 12Z (0600 CST) reprinted from Daily Weather Map: (a) surface, (b) 500 mb.

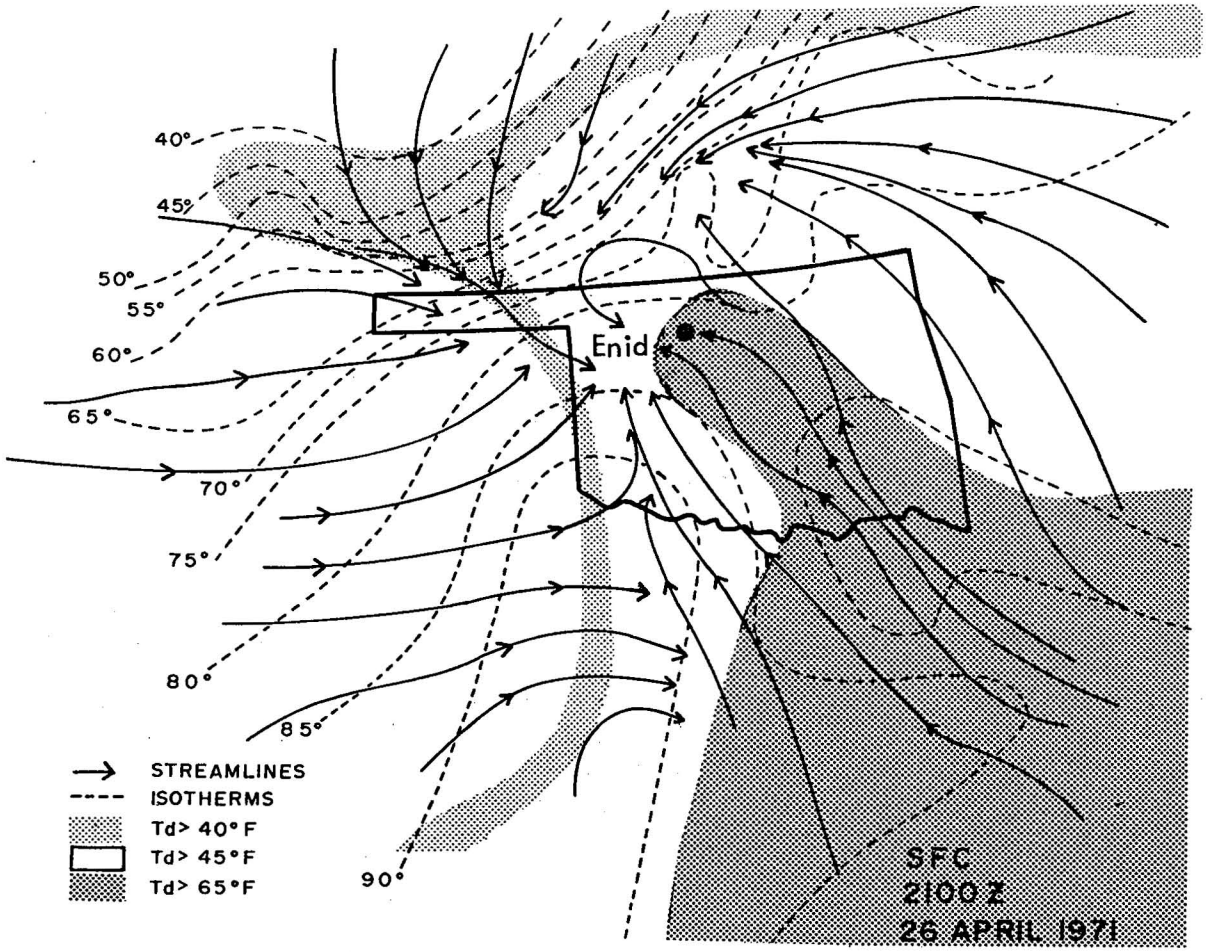



Figure 2. Surface streamline, temperature, and dew point analysis for 26 April 1971 at 1500 CST. The severe thunderstorm is already in progress at Enid.

At 1500 CST, when the first shower developed, the surface map shows strong convergence along the dry line and cold front, especially near Enid, Oklahoma (fig. 2). The intersection of the warm tongue with the moist tongue was also near Enid. A sounding taken just north of Oklahoma City at 1503 CST (fig. 3) shows a typical Type 1 air mass (warm dry air overlying moist air mass) and a lifted index of -3 (Miller, 1967). A strong cap existed there, but probably was less prominent near Enid where horizontal convergence increased the moisture content near the surface and provided sufficient lifting to trigger the storms.

A tornado watch was issued by the National Severe Storms Forecast Center (NSSFC) at 1200 CST, effective from 1600-2200 CST, over the area shown in Figure 4a. The Oklahoma state forecast (fig. 5) was amended to include this watch. Thus, the early evidence indicated that severe weather was possible and the local forecast offices and the public were alerted.

At 1435 CST, the potential for convection was realized as the first thundershower formed southwest of Enid and grew rapidly. It moved toward the north-northeast at about 30 kt, yielding a radar reflectivity factor of $10^5 mm^6 m^{-3}$ by 1503 CST. This vigorous growth to a condition of obvious strength attracted the attention of several radar stations (fig. 5).

The highly favorable meteorological conditions, the previously issued tornado watch (though not yet in effect), and the rapid, almost explosive growth to an intensity exceeding $10^5 mm^6 m^{-3}$ at 0° tilt made it quite obvious that this storm was severe, or soon would be. At 1509 CST, the Oklahoma City NWS Forecast Office issued the first of a series of warnings in connection with the storm (figs. 4 and 5).

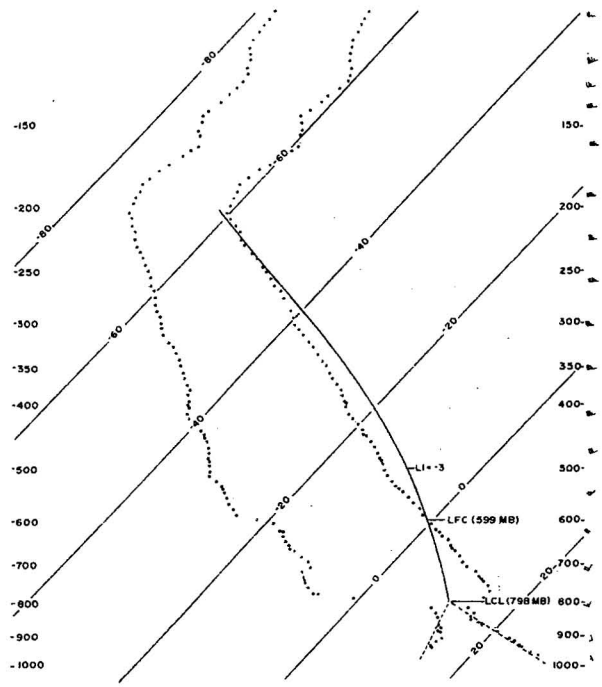
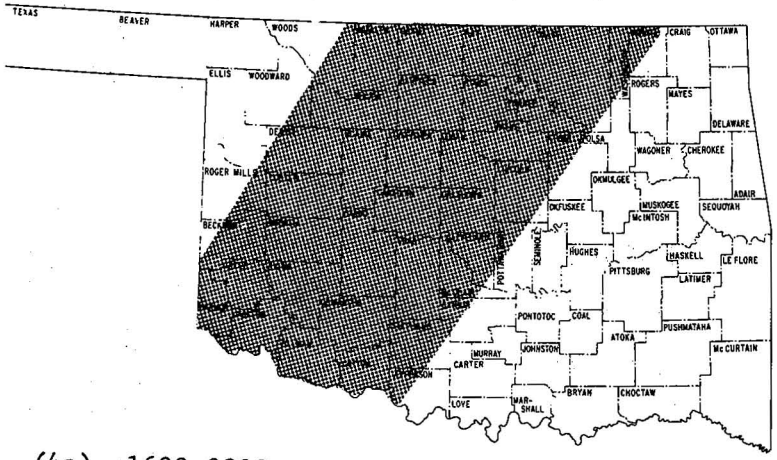



Figure 3. Sounding taken from the NSSL mesonetwork station at Edmond (about 50 n miles SSE of Enid) at 1503 CST, plotted on a skew T-10g P chart.

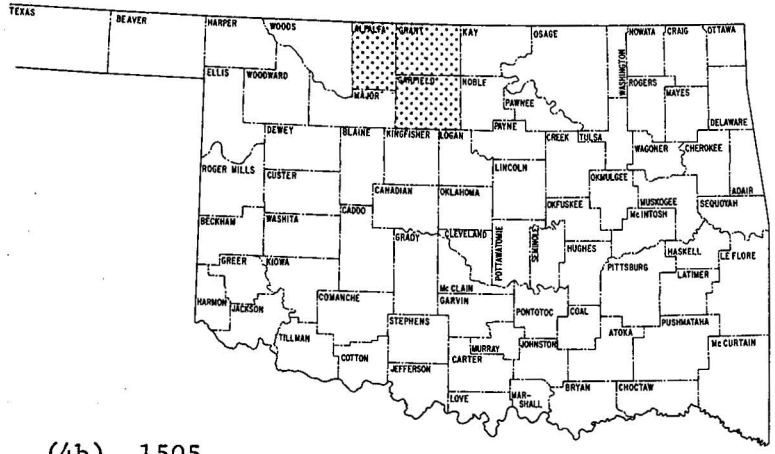
At this time, the storm began to split into two convective areas; the northern area drifted north and weakened, while the southern half continued to intensify as it moved east. Oklahoma City issued a tornado warning at 1535 CST for a tornado "indicated by radar," although in retrospect, this indication is not clearly visible on the photos of the NSSL radar (fig. 6). It was at this time that the severe weather suggested by the high reflectivity was confirmed; Enid was struck by 2 to 4 inch diameter hailstones and wind gusts of 95 mph. These events were reported by telephone to Oklahoma City's radar operator at 1554 CST.

Another warning for a tornado "indicated by radar" came at 1615 CST; this time the sequence of photos (fig. 6) clearly shows a rotating hook echo. A funnel was spotted 5 miles east of Enid and was reported to have uprooted trees when it touched down at 1600 CST in a farmyard. This funnel observation was telephoned to the radar operator at 1613 CST.

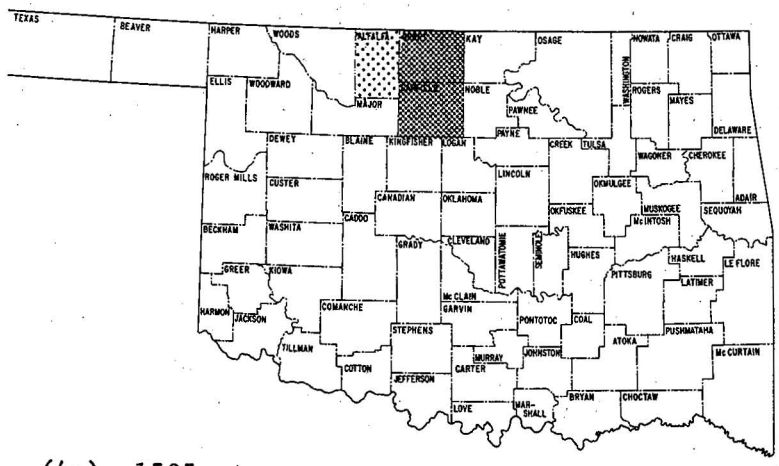
At 1650 CST a second storm formed at the flank of the first one and grew rapidly until the two joined. The axis of the joined cells then rotated 45° from an east-west alignment to a northeast-southwest alignment by 1730 CST. Both cells had core reflectivities greater than $10^5 mm^6 m^{-3}$ during this period. Later, the northern cell--the original Enid storm--began to weaken and its remnants were ingested by the still strong southern cell. The latter cell was still severe when it passed out of NSSL radar display range at 1910 CST.



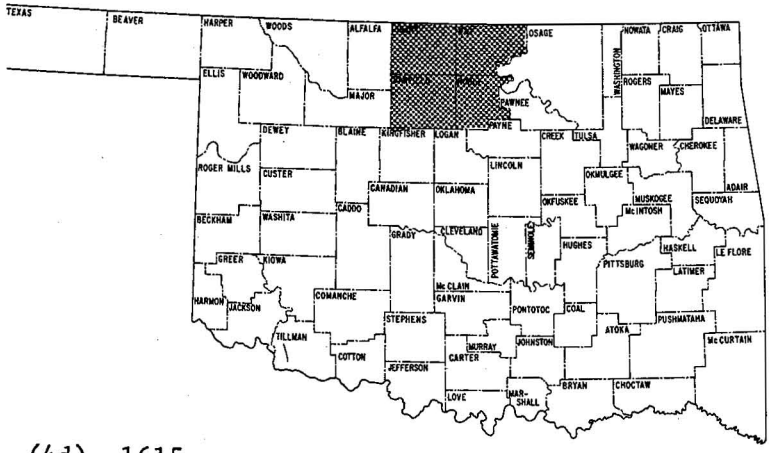

(4a) 1600-2200




(4b) 1505

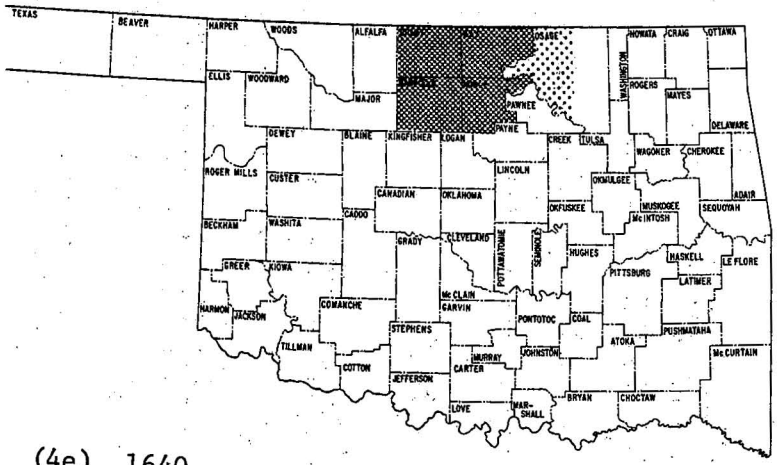



(4c) 1535

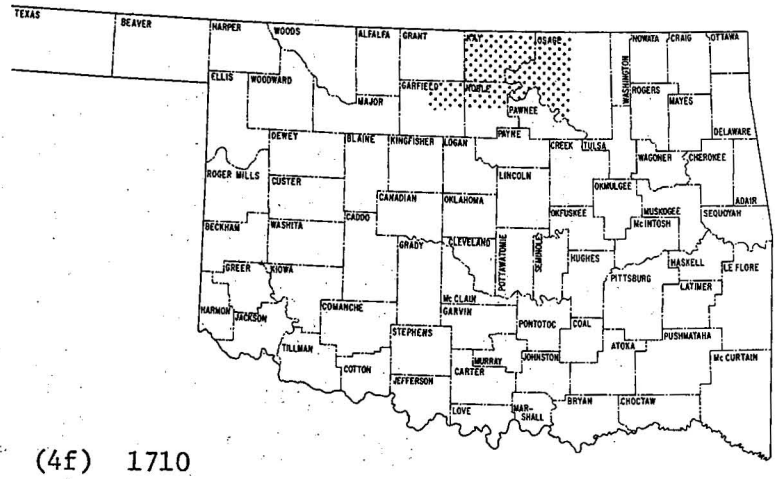



(4d) 1615

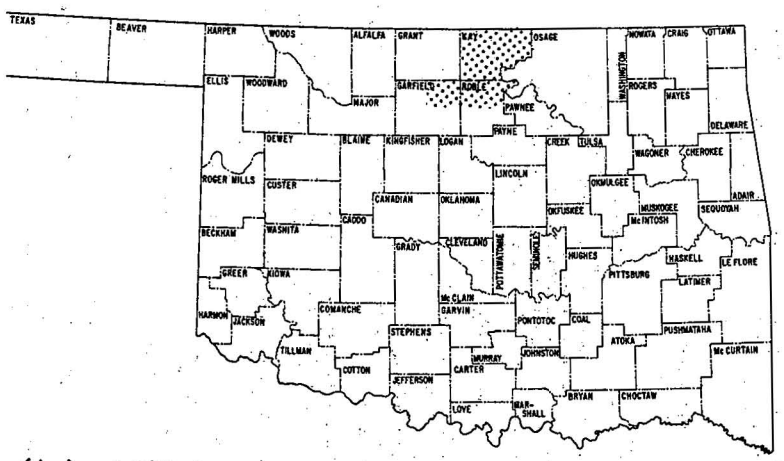
Figure 4. Watch and warning areas: (a) area covered by Tornado Watch Bulletin No. 142 issued by NSSFC (dark shading); (b) through (h) areas covered by severe thunderstorm warnings (light shading) and tornado warnings (dark shading) issued as a result of this particular cell. (All times CST.)



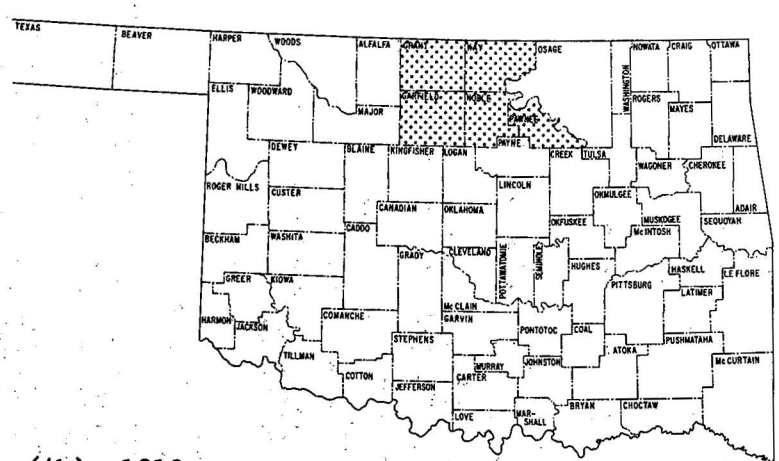

(4e) 1640




(4f) 1710




(4g) 1740




(4h) 1810

Figure 4 Continued

RADAR REPORTS

1500 CST OKC A AMA CELL ABOUT 15 TO 20 MILES SOUTHWEST OF ENID IS LARGE AND STRONG FROM HERE...

OKC A SPS CELL 15 WEST OF ENID AND BLOOMING

OKC A GCK WE HAVE SAME CELL HERE

1515 CST OKC CELL TRW+/NEW 334/64 D5 MT550

1545 CST OKC SD 26/2145
OKC SPL LNO TRW+/NC 2/76 318/62 20W CELLS 1925 MAX TOPS 510 AT 346/64
CELL TRW/NEW 236/73 D6 TOP 310

1645 CST OKC SD 26/2245
OKC SPL CELL TRW+/NC 11/71 D25 MOVMT 2320 TOP 550
LN O TRW+/NC 355/123 355/58 258/39 211/68 15 W CELLS 2220 MAX TOP 520 AT 353/64

1745 CST OKC SD 26/2345
OKC SPL CELL TRW+/NC 20/80 D25 MOVMT 2418 TOP 500
LNO TRW+/NC 358/88 211/29 25W CELLS 2418 MAX TOP 480
CELL TRWU 1/153 D21 APRNT TRW+

1845 CST OKC SD 27/0045
OKC SPL AREA OTRW+/NC 332/66 41/102 48W CELLS 2620 MAX TOP 500 AT 39/85
CELL TRW+/NC 156/14 D30 2620 TOP 490

TUL LN ⊕TRW+/+299/35 314/35 325/48 20W EGG SIZE HAIL AT FAIRFAX OKLA. WHICH IS 299/46 FROM TUL AT 1930 CDT
LNO TRW+/NC 283/80 307/59 15W

WATCHES ISSUED BY NSSFC

1235 CST BULLETIN
TORNADO WATCH NUMBER 142
ISSUED....0135 PM CDT...APRIL 26 1971

THE NATIONAL WEATHER SERVICE HAS ISSUED A TORNADO WATCH FOR EASTERN PORTIONS OF NORTHWEST TEXAS...NORTHWESTERN PORTIONS OF NORTH CENTRAL TEXAS...SOUTHWESTERN AND MOST OF CENTRAL AND NORTH CENTRAL OKLAHOMA AND PORTIONS OF SOUTHEASTERN KANSAS.

THE THREAT OF TORNADOES WILL EXIST IN THESE AREAS FROM FIVE PM CDT UNTIL ELEVEN PM CDT THIS MONDAY EVENING. A FEW SEVERE THUNDERSTORMS WITH LARGE HAIL AND LOCALLY DAMAGING WINDS ARE ALSO FORECAST. THE GREATEST THREAT OF TORNADOES AND SEVERE THUNDERSTORMS IS IN AN AREA ALONG AND SEVENTY MILES EITHER SIDE OF A LINE FROM FIFTY MILES WEST SOUTHWEST OF WICHITA FALLS TEXAS TO SIXTY MILES EAST OF WICHITA KANSAS. PERSONS IN OR CLOSE TO THE TORNADO WATCH AREA ARE ADVISED TO BE ON THE WATCH FOR LOCAL WEATHER DEVELOPMENTS AND FOR LATER STATEMENTS AND WARNINGS....

15:0 CST FPUS1 KOKC 26 1930 AMD
OKC-1230 PM CDT MONDAY

OKLAHOMA.
A TORNADO WATCH IS IN EFFECT FOR MOST OF WESTERN AND CENTRAL OKLAHOMA AND A SMALL PORTION OF NORTHEAST OKLAHOMA FROM 5PM UNTIL 11PM THIS MONDAY EVENING... PARTLY CLOUDY THIS AFTERNOON THROUGH TUESDAY WITH WIDELY SCATTERED THUNDERSTORMS EXCEPT EXTREME NORTHWEST. HIGHS TODAY IN THE 80S. LOWS TONIGHT 40S PANHANDLE TO 62 SOUTHEAST. HIGHS TUESDAY 75. PANHANDLE TO 90 SOUTH.

WARNINGS ISSUED BY OKC WSFO

1505 CST NATIONAL WEATHER SERVICE OKLAHOMA CITY OKLAHOMA
ISSUED 4 05 PM CDT APRIL 26 1971

A SEVERE THUNDERSTORM WARNING IS IN EFFECT UNTIL 520 PM CDT FOR PERSONS IN GARFIEDL GRANT AND ALFALFA COUNTIES IN OKLAHOMA.

A SEVERE THUNDERSTORM WAS INDICATED BY RADAR 8 MILES WEST SOUTHWEST OF ENID OKLAHOMA AT 405 PM CDT. THE SEVERE THUNDERSTORM WAS MOVING TOWARD THE NORTH AT 30 TO 35 MPH.

IF THREATENING CONDITIONS ARE SIGHTED...BE PREPARED TO MOVE TO A PLACE OF SAFETY.

1535 CST BULLETIN
TORNADO WARNING
EANS REQUESTED
NATIONAL WEATHER SERVICE OKLAHOMA CITY OKLAHOMA ISSUED
435 PM CDT APRIL 26 1971

A TORNADO WAS INDICATED BY RADAR NEAR ENID OKLAHOMA AT 435 PM CDT AND IS MOVING TOWARD THE NORTH AT 30 MPH.

IF THREATENING CONDITIONS ARE SIGHTED...BE PREPARED TO MOVE TO A PLACE OF SAFETY.

1615 CST BULLETIN
TORNADO WARNING
EANS REQUESTED
NATIONAL WEATHER SERVICE OKLAHOMA CITY OKLAHOMA

ISSUED AT 5 15 PM CDT APRIL 26 1971

A TORNADO WARNING IS IN EFFECT UNTIL 6 15 PM CDT FOR PERSONS IN KAY...NOBLE...GRANT...AND GARFIELD COUNTIES OF OKLAHOMA. A TORNADO WAS INDICATED BY RADAR NEAR ENID OKLAHOMA AT 455 PM CDT AND IS MOVING NORTHEASTWARD AT 30 MPH.

IF THREATENING CONDITIONS CONDITIONS ARE SIGHTED...BE PREPARED TO MOVE TO A PLACE OF SAFETY.

1640 CST BULLETIN
SEVERE THUNDERSTORM WARNING
IMMEDIATE BROADCAST REQUESTED
NATIONAL WEATHER SERVICE TULSA OKLAHOMA

ISSUED 540 PM CDT APRIL 26 1971
A SEVERE THUNDERSTORM WARNING IS IN EFFECT UNTIL 640 PM CDT FOR PERSONS IN WESTERN OSAGE COUNTY IN OKLAHOMA. A SEVERE THUNDERSTORM WAS INDICATED BY RADAR NEAR PONCA CITY AT 535 PM CDT MOVING TOWARD THE NE AT 20/30 MPH.

IF THREATENING CONDITIONS ARE SIGHTED...BE PREPARED TO MOVE TO A PLACE OF SAFETY.
TO REPORT LARGE HAIL OR DAMAGING WINDS...PLACE AN EMERGENCY COLLECT CALL TO THE TULSA NATIONAL WEATHER SERVICE OFFICE AT THE INTERNATIONAL AIRPORT OR ASK THE NEAREST LAW ENFORCEMENT AGENCY TO RELAY YOUR REPORT TO THE NEAREST NATIONAL WEATHER SERVICE OFFICE.

1710 CST BULLETIN
SEVERE THUNDERSTORM WARNING
IMMEDIATE BROADCAST REQUESTED
NATIONAL WEATHER SERVICE OKLAHOMA CITY OKLAHOMA
ISSUED 6 10 CDT APRIL 26 1971

A SEVERE THUNDERSTORM WAS INDICATED BY RADAR 10 MILES SOUTH SOUTHEAST OF TONKAWA AT 625 PM CDT. THE SEVERE THUNDERSTORM IS MOVING TOWARD THE EAST NORTHEAST AT 20 MPH.

IF THREATENING CONDITIONS ARE SIGHTED...BE PREPARED TO MOVE TO A PLACE OF SAFETY.

1810 CST BULLETIN
SEVERE THUNDERSTORM WARNING
IMMEDIATE BROADCAST REQUESTED
NATIONAL WEATHER SERVICE OKLAHOMA CITY OKLAHOMA
ISSUED 6 10 CDT APRIL 26 1971

A SEVERE THUNDERSTORM WARNING IS IN EFFECT UNTIL 8 15 PM CDT FOR PERSONS IN GRANT GARFIELD KAY NOBLE AND PAWNEE COUNTIES IN OKLAHOMA.

A SEVERE THUNDERSTORM WAS INDICATED BY RADAR FROM ENID TO BLACKWELL OKLAHOMA AT 7 10 PM CDT. THE SEVERE THUNDERSTORM IS MOVING TOWARD THE EAST NORTHEAST AT 20 MPH.

IF THREATENING CONDITIONS ARE SIGHTED BE PREPARED TO MOVE TO A PLACE OF SAFETY.

1907 CST TUL A MKCC 2701072

REF. PIREP 2320Z...WAS HAIL SIZE FOUR INCH ALOFT QQQ PNC HRLYS HAVE NOT RPRTD TORNADO...COULD IT HAVE BEEN AWAY FROM PNC OR WAS IT A FNL CLD QQQ.
SELS

1910 CST BULLETIN
SEVERE THUNDERSTORM WARNING
IMMEDIATE BROADCAST REQUESTED
NATIONAL WEATHER SERVICE OKLAHOMA CITY OKLAHOMA ISSUED
8 10 PM CDT APRIL 26 1971

A SEVERE THUNDERSTORM WARNING IS IN EFFECT UNTIL 9 15 PM CDT FOR PERSONS IN SOUTHEASTERN KAY..EASTERN GARFIELD AND NOBLE COUNTIES IN OKLAHOMA

A SEVERE THUNDERSTORM WAS INDICATED BY RADAR FROM 15 MILES EAST OF ENID TO PONCA CITY OKLAHOMA AT 805 PM CDT. THE SEVERE THUNDERSTORM IS MOVING TOWARD THE EAST AT 25 MPH.

IF THREATENING CONDITIONS ARE SIGHTED...BE PREPARED TO MOVE TO A PLACE OF SAFETY.

Figure 5. Reprints from RAWARC teletype data of radar reports and severe weather watches and warnings, including those shown graphically on Figure 4.

There is ample proof of the storm's severity. Figure 7 (top) represents the "radar hail swath" as a composite of all regions which at some time or other were covered by portions of the storm having digital values of 7 or greater, corresponding to reflectivities of $Z > 10^5 mm^6 m^{-3}$ (Ward, et al., 1965). Dots cover the region experiencing maximum intensity of 7; the dark shading covers 8's, and the stars cover 9's. The midpoints of these intervals corresponding to log Z values of 5.6, 6.2, and 6.6 (Wilk and Kessler, 1970), and to rainfall rates of 4.7, 9.9, and 20.3 inches-$hr^{-1}$, respectively. Some of the gaps in the belt may arise from the 10-min interval between radar measurements. The rainfall rates associated with these reflectivities exceed expected values so that hail is probably responsible for a large fraction of the total reflectivity. Digital values of less than 7 are associated with lower reflectivities and more realistic rainfall rates; hail may still be contributing to the reflectivity, combined with lighter rainfall, but the probability of hail is fairly low and the hailfall is apt to be inconsequential. Thus, the "radar hail swath" identifies the area probably affected by damaging hail.

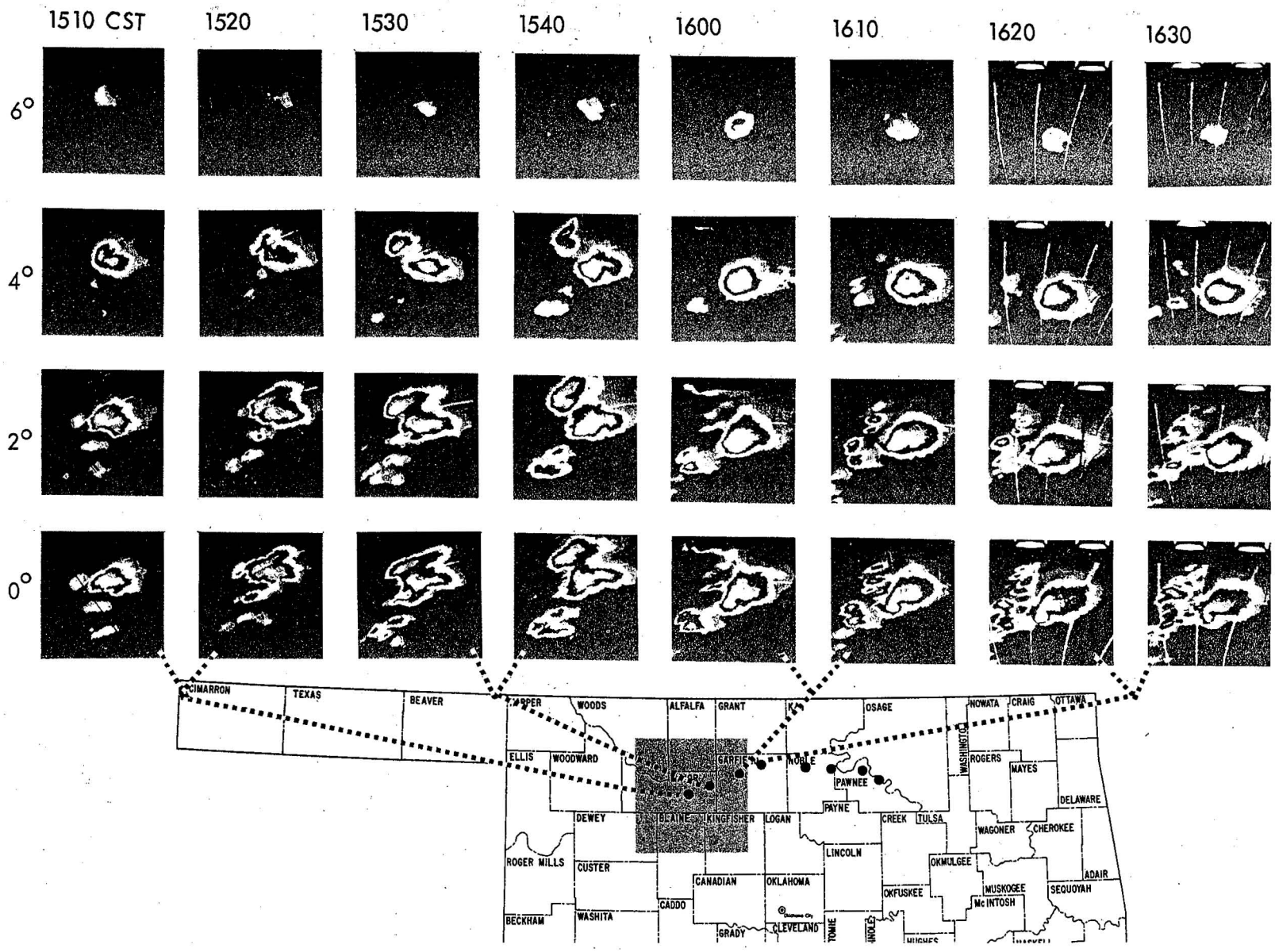
Figure 7 (bottom) shows the location of 12 weather reports near the path taken by the centroid of the storm. The dots within the line represent the locations at 10-min intervals. Solid dots represent the principal storm; open circles (connected by dashed lines) represent the northern component of split radar cell. The apparent retrograde motion at 1640 CST is due to the new cell joining to form a tandem (see fig. 6). There is good agreement among the centroid path, the "radar hail swath," and the locations of severe weather reports. These reports verify that a severe hailstorm did occur in the region shown by the "radar hail swath," particularly those areas indicated by digital values of 8 or 9. Although the largest reported hail, which fell in Enid, was associated with only 7's, the hail that fell in the areas covered by 8 or 9 came in considerably greater quantity. Significantly, most of the severe weather events occurred south of the echo centroid, which is probably related to the southward projection of the hook echo. Strong winds may also occur beneath dense clouds east of the hook, where precipitation and radar echo have not yet formed in the northward flowing moist air. The severe weather reports, with their corresponding location numbers are as follows:

1. 1530 CST (north part of Enid) - Hailstones averaging 2 inches and ranging up to 4 inch diameter combined with 95 mph winds to cause heavy damage estimated to be about $2,000,000.

2. 1530-1535 CST - 1/4 inch hail was reported by a volunteer observer who added "the roar of hail falling to the southeast was clearly audible for 20 minutes."

3. 1600 CST (5 miles east of Enid) - A tornado was sighted and was reported to have touched down in a farmyard, uprooting grown evergreens.

4. 1610-1625 CST - Five minutes of 1/4 to 3/4 inch hail was followed by damaging winds described as "a tornadic gust." It is unknown whether a tornado or funnel aloft was actually present.


1510 CST
1520
1530
1540
1600
1610
1620
1630
6°
4°
2°
0°
CIMARRON
TEXAS
BEAVER
WOODS
ALFALFA
GRANT
OSAGE
NOWATA
CRAIG
OTTAWA
ELLIS
WOODWARD
GARFIELD
NOBLE
PAWNEE
WASHINGTON
ROGERS
MAYES
DELAWARE
PAYNE
DEWEY
BLAINE
KINGFISHER
LOGAN
CREEK
TULSA
WAGONER
CHEROKEE
LINCOLN
ROGER MILLS
CUSTER
OKMULGEE
ADAIR
CANADIAN
OKLAHOMA
MUSKOGEE
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McINTOSH
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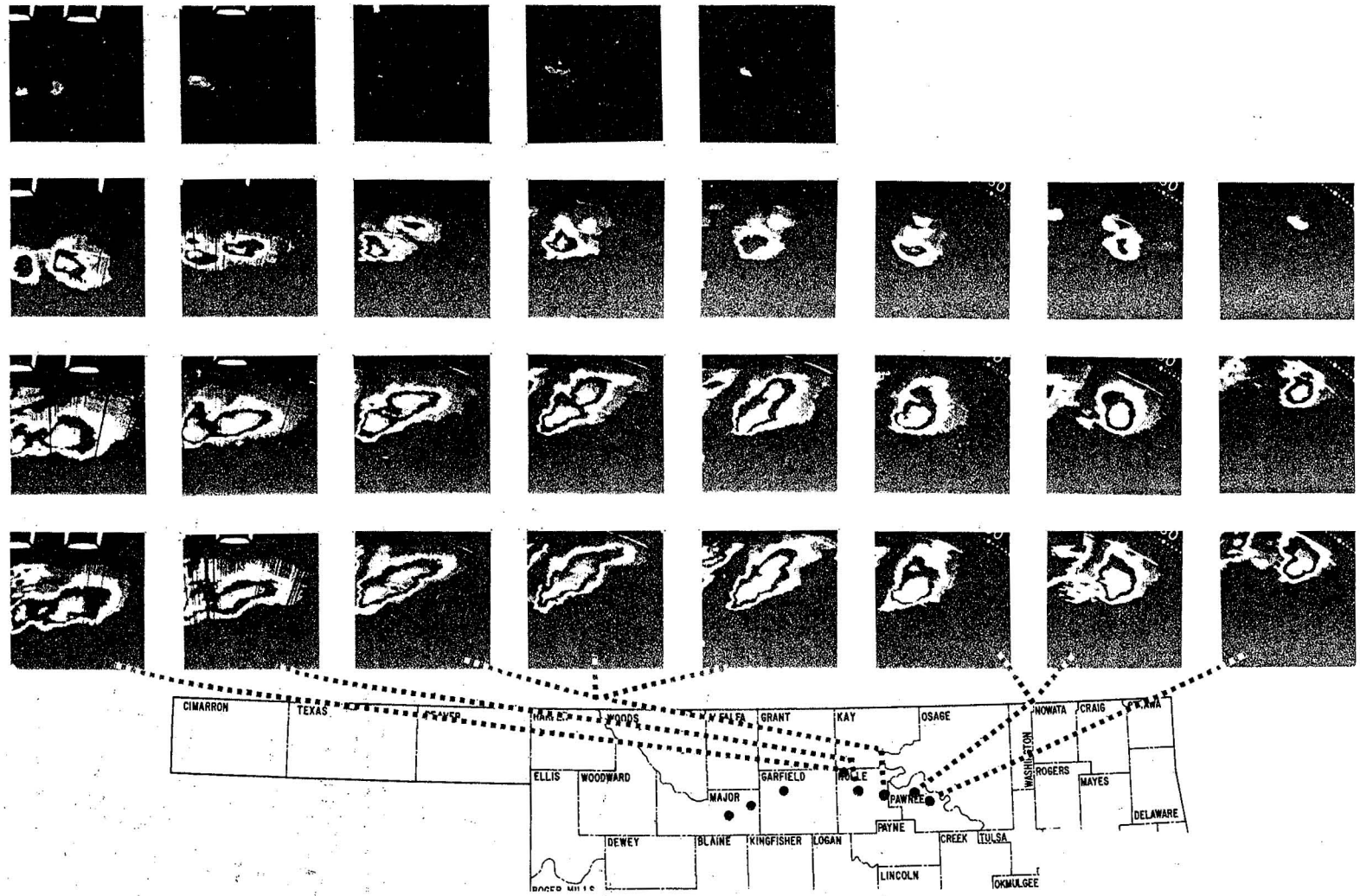


Figure 6. Radar anatomy of the severe thunderstorm: PPI displays show cell cross section at 0°, 2°, 4°, and 6° of antenna tilt at times (CST) shown. Dotted lines connect photos to corresponding positions on accompanying map of northern Oklahoma. Total area covered by first photo is also shown on map (shaded square).

5. 1834-1841 CST (Blackwell) - A light fall of 1/4 to 1/2 inch hail fell; the core of the storm was reported to have been farther south.

6. Time unspecified - Roads were reported to have been slick with hail in the area between Ponca City and Marland.

7. Time unspecified - An unofficial 9 to 10 inches of rain fell (some of which may have come from later storms). West of Marland, baseball-sized hail drifting 18 inches deep was reported.

8. Time unspecified - Hail ranging from 1/4 to 2 inches fell along with 1 to 1 3/4 inches of rain.

9. 1830-1845 CST - Damaging hail was reported.

10. 1730-1800 CST (about 15 n miles SW of Fairfax) - 3/4 to 1 1/2 inch hail piled up 1 inch deep over a sizable area, damaging roofs and windows, and ruining the wheat.

11. 1830-1845 CST - 1/2 inch hail with scattered 1 1/2 inch hailstones was accompanied by damaging winds.

12. 1830-1845 CST - Tennis ball sized hail was reported.

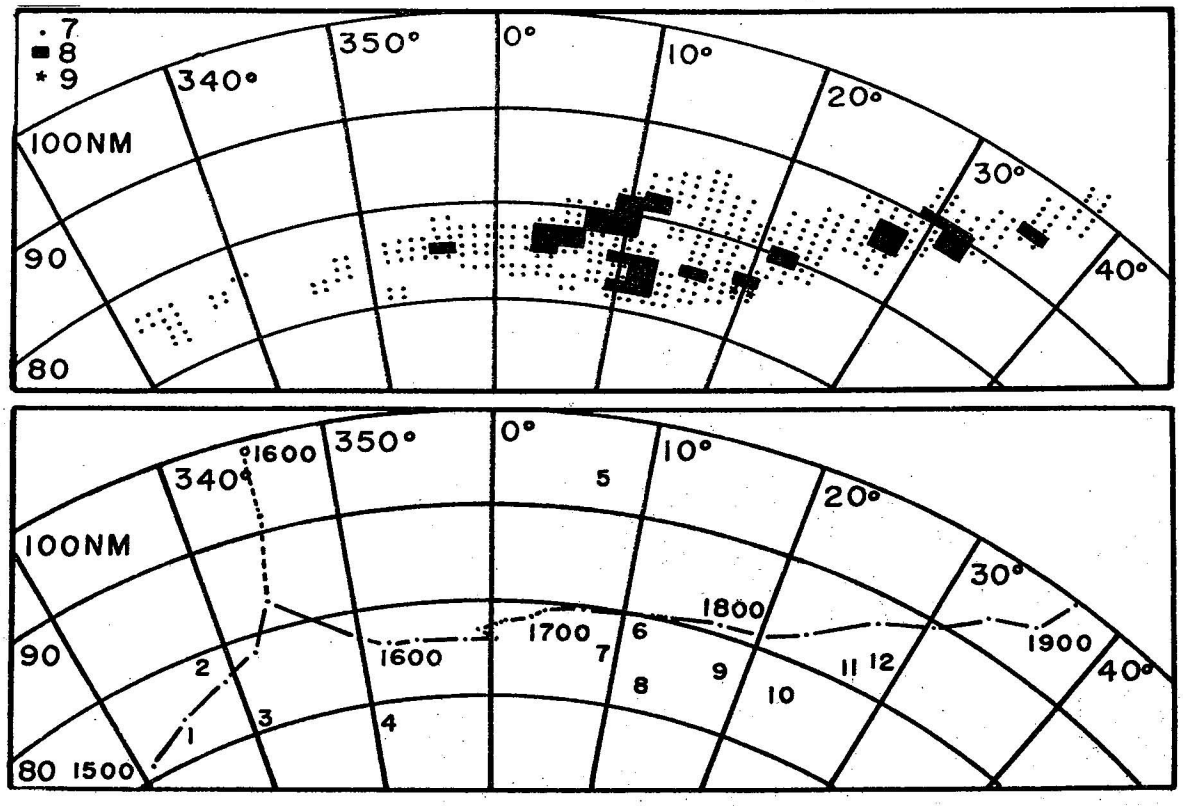


Figure 7. Path of the storm (range and azimuths are from NSSL radar). Top: "Radar hail swath" where digital B-scan display contained values of 7 or greater. Bottom: Path of centroid of storm and location of observer reports (marked by numbers 1 - 12) related to the storm.

The detection and tracking of this severe storm was somewhat more "cut-and-dried" than those usually experienced by forecasters and radar operators, with the consequence that the issuance of watches and warnings became a relatively simple, straightforward process. In this case, with the storm isolated and the intense centers easily tracked, the areas indicated in the warnings might have been even more precise and the persistent centers of heavy rain specified as they moved consistently through the affected counties. With greater variety in message format, the forecaster could expand or restrict the warning area as his knowledge warranted. Of course, the extraction and communication of highly detailed tracking and warning information for each severe storm core has important implications on staffing and data processing requirements.

Not all data are so unambiguous, but this case provides a good illustration of how, in theory, the WSR-57 contour display can be interpreted in light of the background meteorological data. The sequence of events may be summarized as follows:

1. The surface and upper air analysis, along with the sounding, clearly indicated a high potential for severe weather in western and central Oklahoma. Consequently, a watch was issued, and the radar was monitored continuously in response to the watch.

2. A single cell formed and grew very rapidly into a large storm with a core reflectivity exceeding $10^5 mm^6 m^{-3}$. This "core" can be identified at a glance on the NSSL WSR-57 contour display by the bright "fifth-level" contour. The equivalent means of identification on the old type of display is by successive attenuation of the signal, a more time-consuming process. This cell could be considered to be severe with a high degree of confidence because it attained a high intensity in a region already having a recognized high potential for severe weather. (Also, intensification was expected since the diurnal peak in convective heating was yet to come.) The direct indication provided by the strong radar reflectivity was hail: strong winds were inferred on a "where there's smoke there's fire" basis.

3. At 1615 CST a pronounced hook echo formed with obvious rotation indicated in the sequence through 1645 CST (fig. 6). A hook echo on the new contour display has the same meaning as a hook echo on older displays, but the former is backed by the level 5 contour, lending extra credence to the implication of a tornado in progress. Note also that the hook shape is best outlined by the level 3 contour; on linear receiver displays this feature could have been missed entirely if the operator failed to go through the attenuation procedure at the right time.

4. This storm could be considered severe--and warnings continued--until the core reflectivity clearly fell below $10^5 mm^6 m^{-3}$. In this case echoes greater than $10^5$ were still present as the storm moved beyond 100 mile range.

5. The occurrence of severe weather was unusually well reported although most reports were too late to do more than confirm the warning. A continuous

swath of hail--often heavy--coincided with the track of the core that had a reflectivity greater than $10^5 mm^6 m^{-3}$. Although this storm was clearly visible to the forecaster and the public, verification came sporadically. In many cases, reports of surface observations will be even less frequent, especially with storms in isolated regions. When verification by observers is lacking, it is best to trust the radar intensities. If a storm passes over a community without eliciting a few reports, a reevaluation may be necessary.

## CASE 2 - 28 APRIL 1971

Two days after the occurrence of the severe storm at Enid, another severe thunderstorm struck Duncan at 2129 CST with hail, three reported funnels, and winds estimated at 80 mph which destroyed six mobile homes and caused considerable damage to trees, utility poles, roofs, and windows.

Unlike the Enid storm, the Duncan storm struck without warning and did not occur in an area where the potential for severe weather was easily recognized. The radar reports issued from Oklahoma City with the aid of displays of the linear radar receiver tended to underrate the occasional strong cells that traveled along a line of generally weak showers; however, the contoured display photographed at NSSL clearly showed two cells that were very intense before the occurrence of the severe weather.

The surface analyses at 1200 CST (fig. 8) show that the region having the greatest potential for severe weather was from western to north central Texas. The surface pressure and frontal analysis (fig. 8a) is characterized by a ridge of high pressure oriented north-northwest to south-southeast through northeastern Oklahoma with a trough extending northward from Texas. The front was diffuse, marked mainly by convergence of the easterly and northeasterly winds over Oklahoma with the southeasterly winds carrying moisture from the Gulf of Mexico (fig. 8b). Another line of convergence was created by southwesterly winds flowing from southwest Texas to meet the southeasterly flow from the gulf. The strongest convergence located on the front was southwest of the line from Childress to Wichita Falls. This was marked by a pressure trough and a dry line (fig. 8c).

A warm ridge of 850 mb extended north-northwest from Mexico and southwestern Texas into New Mexico at 1800 CST (fig. 9). There was a pocket of moist air on the east side of the warm tongue with Del Rio and Abilene reporting dewpoints of 10°C and 12°C, respectively. At 500 mb that morning (fig. 10) a short wave associated with a cutoff low over the Southwest resulted in positive vorticity advection over western Texas.

The combination of strong low-level convergence, upslope flow, advection of warm moist air at 850 mb, and vorticity at 500 mb was favorable for development of severe weather in the Texas panhandle. Consequently, a tornado watch was issued by NSSFC for that region at 1135 CST (fig. 11). Later, when heavy activity was confined to the southern end of the watch area, it was replaced at 1705 CST by a new tornado watch covering portions of north central Texas, valid from 1700 CST to 2300 CST. This watch was placed along

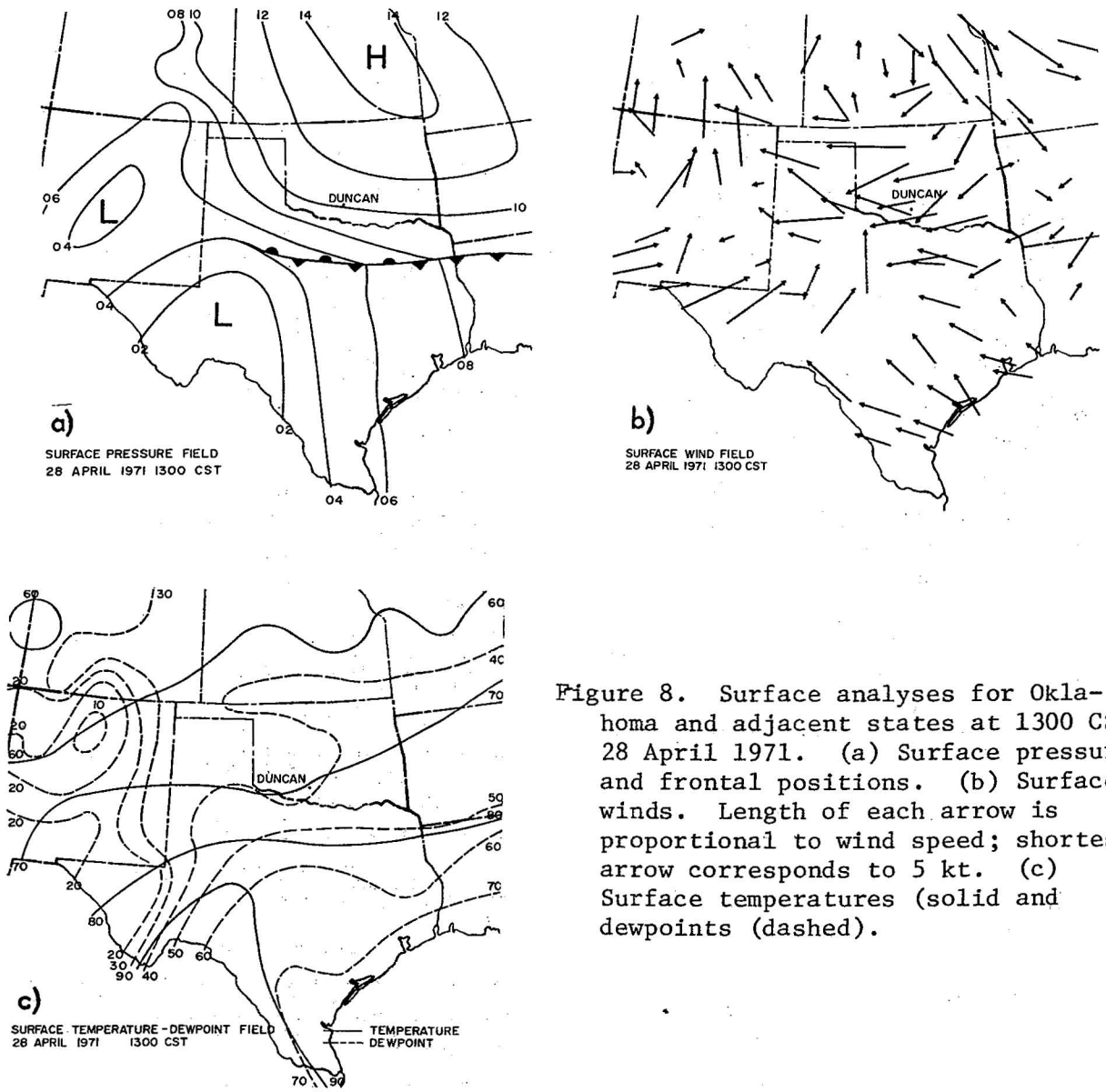


Figure 8. Surface analyses for Oklahoma and adjacent states at 1300 CST 28 April 1971. (a) Surface pressure and frontal positions. (b) Surface winds. Length of each arrow is proportional to wind speed; shortest arrow corresponds to 5 kt. (c) Surface temperatures (solid and dewpoints (dashed).

the frontal boundary where considerable severe activity erupted later during the evening. The extent of this activity is described by an excerpt of the Fort Worth radar summary at 2045 CST (fig. 12) and illustrated by the NSSL radar at 1905 CST (first panel, fig. 13).

While most attention was focused on the activity in north central Texas, a line of weak thundershowers developed from the vicinity of Childress to McAlester. Subsequently, isolated strong cells developed in the line near Childress and moved east.

After comparing the radar reports from several stations and weather statements from NWS in Oklahoma City (fig. 12) with the actual contour display of the line by NSSL radar (fig. 13), we conclude that the strengths of these

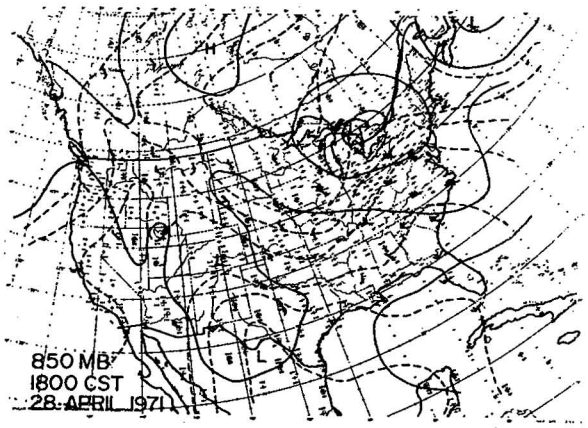


Figure 9. 850 mb analysis for United States at 1800 CST 28 April 1971 (reproduced from facsimile transmitted by NMC).

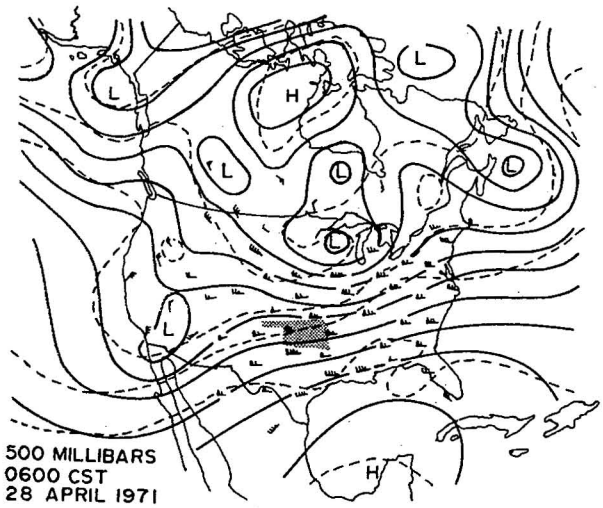


Figure 10. 500 mb analysis for United States at 0600 CST (reproduced from Daily Weather Map).

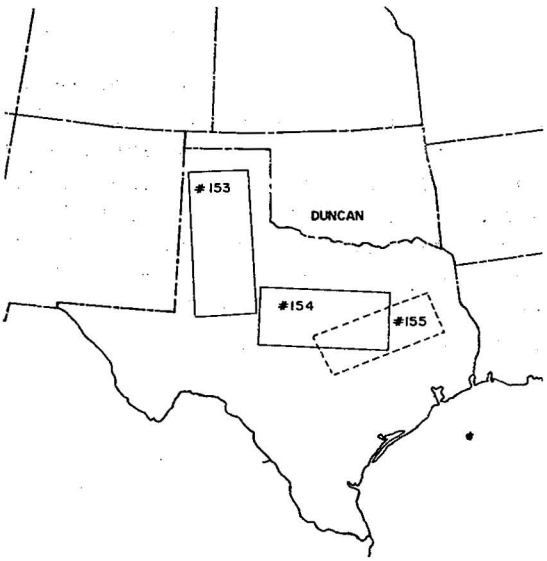


Figure 11. Outline of severe weather watches issued by NSSFC on 28 April 1971. Tornado Watch No. 153, issued at 1135 CST, was valid from 1300 CST to 1900 CST. Tornado Watch No. 154, issued at 1705 CST, was valid from 1700 CST to 2300 CST and replaced Tornado Watch No. 153. Severe Thunderstorm Watch No. 155, issued at 2225 CST, was valid from 2300 CST to 0300 CST 29 April 1971.

SD 290245Z

ICT AREA ⦶ TRW-/- 119/120 160/185 199/205 216/90 CELLS 2530
MAX TOP 260 AT 186/86
AMA AREA ⦶ TRWU 101/133 99/167 138/138 0000
OKC LN ⦶ TRW/NC 120/44 240/103 20 W CELLS 2420 MAX TOP 370
AT 227/68
GSW LN⦶ TRWU 18/135 323/130 15W CELLS 2625

GSW SPL CELL TRW+/NC 209/60 D25 2730 TOP 550 HOOK INDCD AT 210/7
CELL TRW+/NC 116/48 D25 2730 TOP 500 HOOK INDCD 131/54
CELL TRW+/NC 151/56 D20 2730 TOP 540 A INDCD
CELL TRWU 230/135 D15

OKLAHOMA CITY RADAR WEATHER 7 45 PM CDT

ANOTHER LINE OF THUNDERSTORMS WITH MOSTLY LIGHT RAIN ABOUT 2Ø MILES WIDE EXTENDS FROM FORT COBB TO THE RED RIVER SOUTH OF FREDERICK. THIS LINE IS MOVING TOWARD THE NORTH AT ABOUT 2Ø MPH.

OKLAHOMA CITY RADAR WEATHER 8 45 PM CDT

RADAR INDICATES A LINE OF THUNDERSTORMS ABOUT 2Ø MILES WIDE WITH MODERATE TO BRIEF HEAVY RAIN AND POSSIBLY SOME SMALL SCATTERED HAIL EXTENDING FROM SHAWNEE TO RUSH SPRINGS TO THE RED RIVER SOUTH OF EL DORADO. THIS LINE IS MOVING TOWARD THE NORTHEAST AT ABOUT 2Ø MPH.

OKLAHOMA CITY RADAR WEATHER 9 45 PM CDT

RADAR INDICATES A LINE OF THUNDERSTORMS ABOUT 2Ø MILES WIDE WITH LIGHT TO MODERATE RAIN WITH THE CENTER OF THE LINE EXTENDING FROM 15 MILES SOUTH OF SHAWNEE TO 1Ø MILES SOUTH OF MANGUM. THE LINE IS MOVING TOWARD THE NORTHEAST AT ABOUT 2Ø MPH.

OKLAHOMA CITY RADAR WEATHER 1Ø 45 PM CDT

THE HEAVIEST THUNDERSTORMS IN THE AREA ARE ALONG A LINE FROM DUNCAN TO PAULS VALLEY. BRIEF HEAVY RAIN SOME SMALL SCATTERED HAIL AND STRONG SURFACE WIND CAN BE EXPECTED IN THIS AREA.

THE AREA IS MOVING EASTWARD AT ABOUT 2Ø MPH.

Figure 12. Reproduction of selected radar reports from several stations and radar weather summaries issued by OKC during the evening of 28 April 1971.

cells were underestimated by the forecaster. The severe weather reports support such a conclusion. A volunteer observer at Frederick (235 degrees/91 n miles from NSSL) mailed in a report of hailstones averaging 3/4 inch in diameter covering the ground at 1900 CST. A few stones were 1 1/2 inches in diameter. The radar echo from this storm had a maximum reflectivity factor greater than $10^5 mm^6 m^{-3}$ at 1905 CST. A statement from Oklahoma City issued at 1945 CST indicated the possibility of small hail from this storm.

The cell at Frederick later weakened ($Z > 10^4 mm^6 m^{-3}$), but another strong cell appeared on the NSSL radar scope in the southwest. This new cell strengthed as it moved eastward with the maximum reflectivity exceeding $10^5 mm^6 m^{-3}$. As it approached Duncan (205 degrees/52 n miles from NSSL), it appeared to rotate; this is clearly indicated in the last four panels of Figure 14.

The most severe feature of the storm at Duncan was the very strong wind gusts. The ground was covered by hail in some places, but stones were generally 1/4 to 1/2 inch, with a few as large as 3/4 inch. The wind, however, caused widespread heavy damage, especially to trees and utility poles. Although funnels were reported, it is unlikely they were responsible for the general pattern of damage. The combination of outflow from the storm, convergence in the circulation about that portion of the storm, and the forward movement of the storm (35 kts), could account for the estimated 70 kt wind velocity at Duncan.

Duncan received no warning or indication of anything more intense than moderate rain, until after the storm had struck. Several factors were responsible for the failure to identify the storm as a severe one: (1) the absence of any watch (the nearest one, No. 154, was about 100 n miles away; (2) the large echo-free region between the principal activity in Texas and the thunderstorm line producing the Duncan storm (first panel, fig. 13), which caused radar operators to disassociate the activity in Oklahoma from the anticipated activity in Texas; (3) the previous history of only light activity on the line (with the exception of the Frederick storm); (4) the Duncan storm traveled over generally open country before striking the Duncan area; and (5) radar operators having only linear receiver displays.

The contour display shown in Figure 12 permits severe storms to be identified at a glance; if the history of the Frederick storm were added, the potential of the Duncan storm would have been obvious, notwithstanding factors (1), (2), and (4). With linear receiver displays, a forecaster almost has to anticipate a severe storm and then go through the attenuation procedures needed for a positive identification.

Since about one-third of all tornadoes occur in a valid watch area (Galway, 1967), rapid diagnosis of the storm intensities is essential. In a marginal meteorological situation such as the one being discussed, the question of "over-warning" arises. A compromise might be found in the existing terminology used by NSSFC. One helpful phrase, used in a public severe weather watch, is that "persons in or near the watch area keep in touch..." Whether

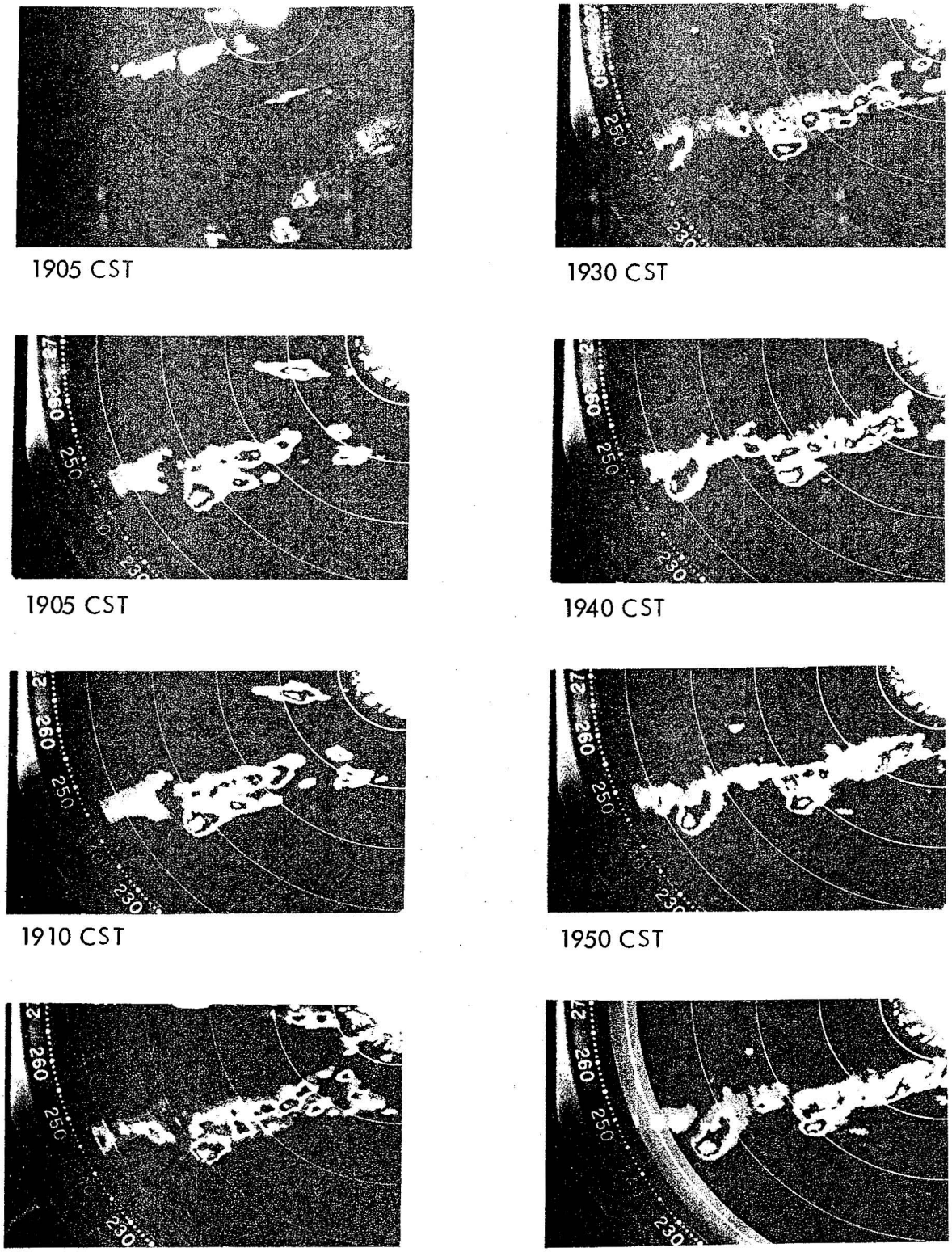


Figure 13. NSSL radar display 1905 CST - 2000 CST. First panel (1905 CST) shows moderate line in SW Oklahoma and active line in north-central Texas; range marks are at 50 n mile intervals. Remaining panels show contour display; range marks are at 20 n mile intervals.

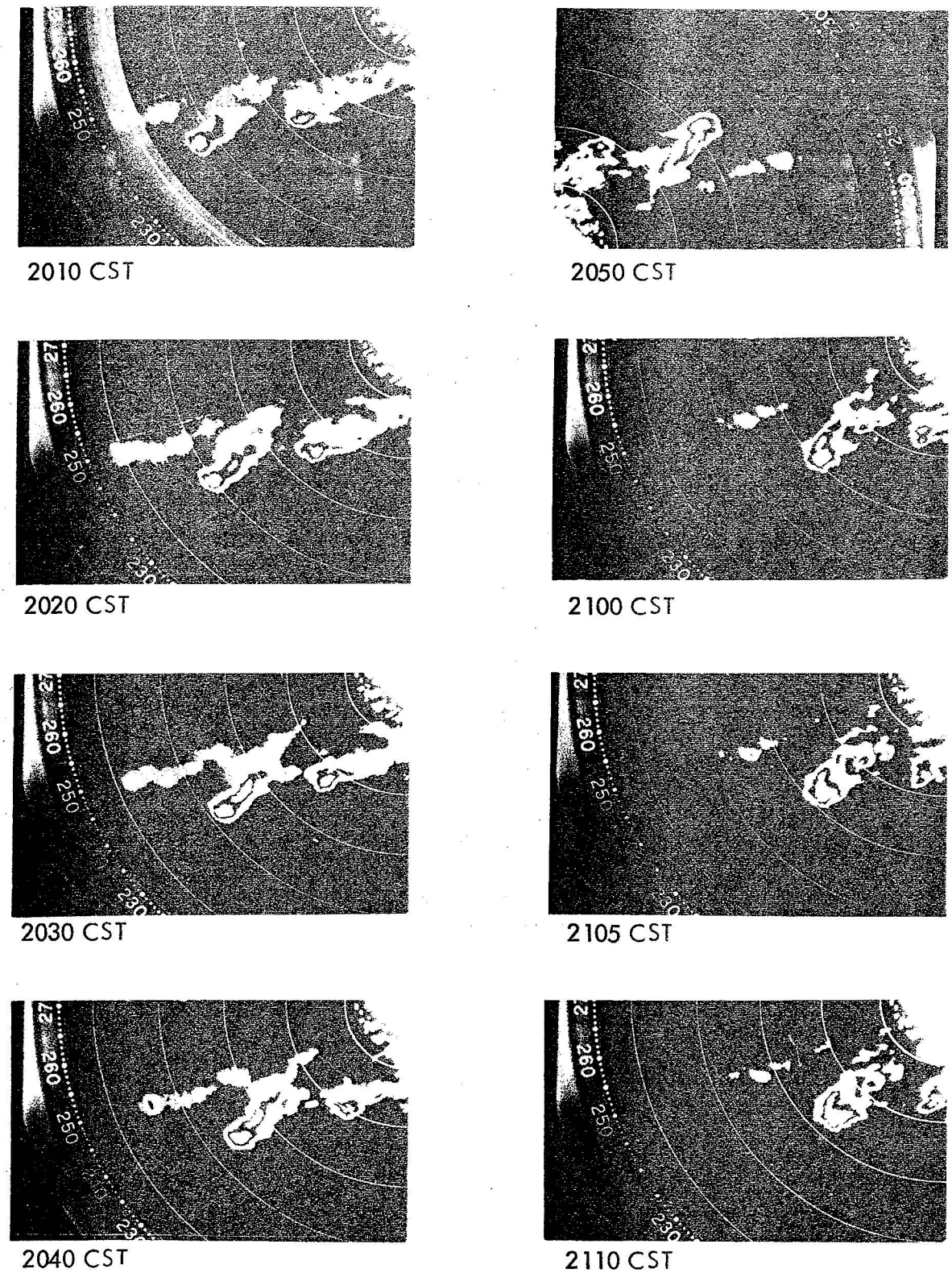


Figure 14. NSSL radar display 2010 CST - 2110 CST. Last panel shows south edge of strong cell approaching Duncan (250 degrees/52 n miles).

Duncan could have been considered to be "near" Watch No. 154 is a matter of judgment for radar operators and forecasters. The second phrase, especially when used with the first, can be quite valuable: "cells may approach severe limits..." This phrase may appear in NSSFC's convective outlook or in Section D of an aviation watch bulletin under the heading "Other Watch Info." When it appears, it can be interpreted as a "radar operator's watch."

## CONCLUDING REMARKS

Several features are common to the two severe thunderstorms discussed in this paper. Although the storm that struck Enid was the more severe, both showed reflectivity factors of $10^5 mm^6 m^{-3}$ or greater on the NSSL contour display. Photo sequences of the displays clearly show rotation in both cells. These common features lead to an important conclusion: both storms were clearly identifiable on the contour display as being potentially severe, and surface reports substantiated these judgments.

The investigation of the circumstances surrounding each storm shows the storm that struck Enid developed rapidly under conditions that were obviously very nutritious for developing thunderstorms. Such a rich diet was unavailable to the storm that surprised Duncan. Consequently, the development of the Enid storm was closely watched and the severe activity anticipated, but the Duncan storm was overlooked.

The recognition of meteorological conditions favorable for severe weather, expressed by NSSFC through a severe weather watch, can contribute to the recognition of echoes indicative of potentially severe thunderstorms. This is as it should be; however, the absence of a watch does not assure that any storm appearing on the radar scope will not become severe.

The anticipation of severe weather primarily serves to increase the lead time for a warning by increasing the forecaster's confidence that a strong cell ($Z > 10^5 mm^6 m^{-3}$) will produce severe weather. A reflectivity factor greater than $10^4 mm^6 m^{-3}$ indicates a possibility of severe weather developing at any time, although more information must be considered when a watch is absent.

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The NSSL Technical Memoranda, beginning with No. 28, continue the sequence established by the U. S. Weather Bureau National Severe Storms Project, Kansas City, Missouri. Numbers 1-22 were designated NSSP Reports. Numbers 23-27 were NSSL Reports, and 24-27 appeared as subseries of Weather Bureau Technical Notes. These reports are available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151, for $3.00, and a microfiche version for $0.95. NTIS numbers are given below in parentheses.

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