NOAA Technical Report ERL 435-FSL 1

Meteorological Analysis of the Cheyenne, Wyoming, Flash Flood and Hailstorm of 1 August 1985

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U.S. DEPARTMENT OF COMMERCE
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Forecast Systems Laboratory
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C.F. Chappell* and D.M. Rodgers

ABSTRACT. Analysis of a devastating storm that struck Cheyenne, Wyoming, on 1 August 1985 shows that the storm began as an east-west multicellular system just south of the city near the summit of the Cheyenne Ridge. This system developed in a conditionally unstable air mass that formed over southeast Wyoming as a southeasterly flow of very moist air at low levels became juxtaposed with an area of steepening lapse rates to the west. Early cells drifted slowly northward in agreement with the pressure-weighted vector mean wind of the environment. New convective growth on the southwest flank of this multicellular system eventually produced a wave-shaped convective system, which rapidly developed supercell structure. As the supercell began to rotate, the storm became stationary over the city for nearly 2 hours. This lack of motion is believed to have been due to helicity, which promoted the transverse propagation of the supercell's updraft at a rate that counteracted the effects of the vector mean wind of the environment. The storm began to move southeastward with the arrival of a short-wave trough and soon dissipated as it encountered increasingly stable conditions. The results of the study suggest that the eastern foothills of the Rocky Mountains and the adjacent high plains may be particularly vulnerable to this type of storm. Deep convection frequently occurs over this area when moist air arrives from the Great Plains, driven by a low-level easterly jet. The combination of strong low-level easterly flow topped by weak middle-level southerly flow can apparently produce sufficient wind shear for supercell formation, while producing a vector mean wind for the environment that gives little or no eastward motion relative to the ground.

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1. INTRODUCTION

A devastating flash flood and hailstorm struck Cheyenne, WY, during the early evening of 1 August 1985. Twelve persons lost their lives, and damage to homes, cars, roads, and business establishments was estimated to be in excess of $65 million. Total rainfall was as much as 20 cm in parts of the city (Fig. 1), accumulating in about a 3-h period. Rainfall of 15.4 cm was officially measured at the Weather Service Forecast Office (WSFO) in Cheyenne; 8.9 cm fell in the 1-h period from 0200 to 0300 GMT, 2 August 1985 (subtract 6 h to convert to local daylight time). These rainfall amounts were new 24-h and 1-h records for Wyoming. Other severe weather attended this storm. Hail up to 5 cm in diameter pummeled parts of the city, reaching depths of 30 cm. Hail was carried to low-lying areas by surface runoff, collecting into 1-2 m drifts, and was not completely melted 2 days later. A few funnel clouds were also observed during the storm, and two short-lived tornadoes were reported.

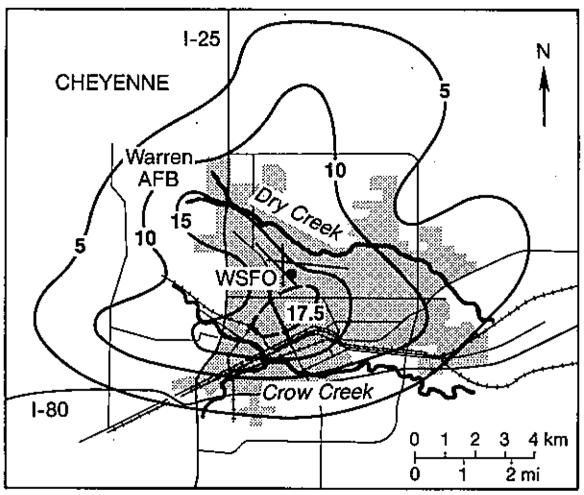


Figure 1. Twenty-four-hour rainfall totals (cm) ending 1200 GMT, 2 August 1985. Shading indicates Cheyenne metropolitan area. National Weather Service Forecast Office (WSFO) location is indicated. Maximum rainfall was 17.5 cm (dashed contour).

Local flooding began soon after the onset of rain and affected most of the city. Flooding was particularly severe along Dry Creek in northern Cheyenne, along Crow Creek in the southern part of the city, and in the downtown area. City and State government buildings in downtown Cheyenne sustained considerable damage. Seventy injuries were attributed to this disaster, and of the dozen deaths, 11 were due to drowning, 9 of these occurring in association with automobiles.

Heavy rains and flash flooding have been a growing problem for the eastern foothills of the Rocky Mountains and the plains area immediately to the east. Increases in population and resultant urbanization in many of the watersheds that drain eastward out of the foothills are creating many potentially serious flash flood situations. Several of the worst flash floods in this area have been investigated, including the Rapid City flood of June 1972 (Dennis et al., 1973; Maddox et al., 1978), the Big Thompson Canyon flood of July 1976 (Maddox et al., 1977), and the Palo Duro Canyon flood of May 1978 (Bellville et al., 1980). These studies have helped to identify certain synoptic weather patterns that favor the development of slowly moving, or nearly stationary, thunderstorm systems that produce copious amounts of rain.

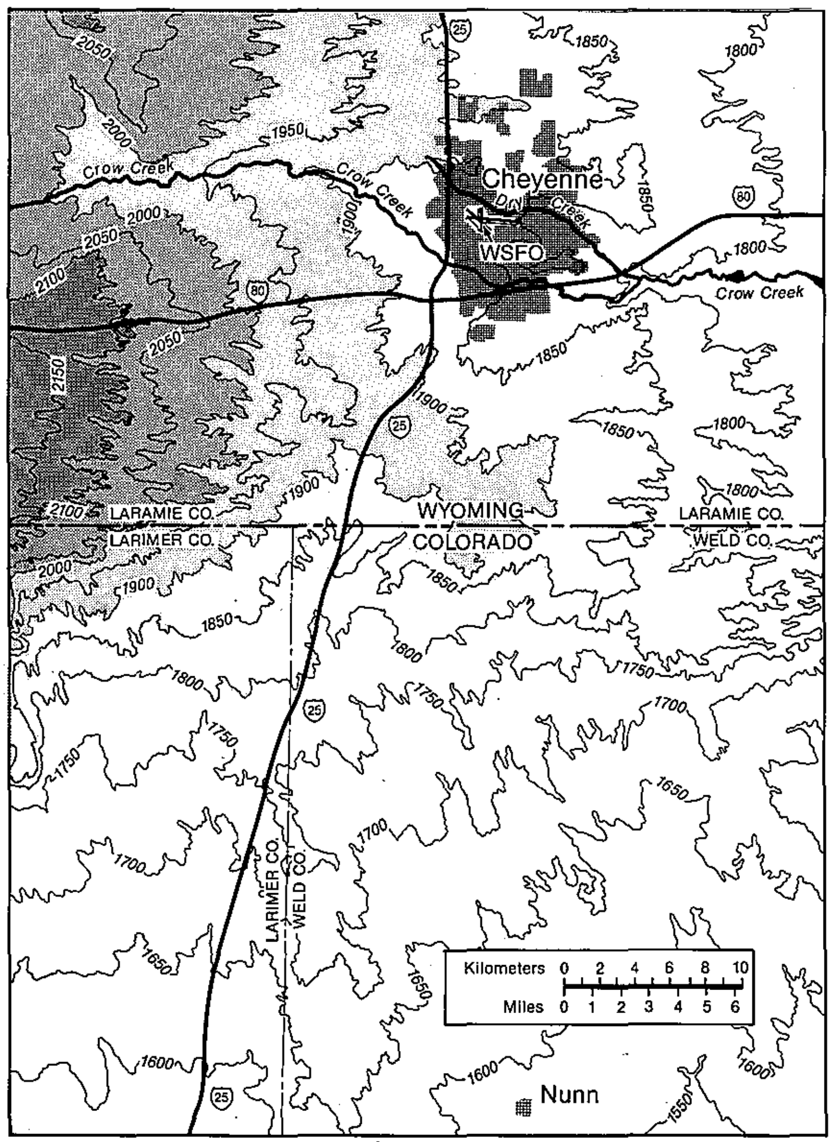


Figure 2. Terrain height contours (m) for southeastern Wyoming and northeastern Colorado.

2. TOPOGRAPHY OF THE CHEYENNE AREA

There is some evidence that terrain (Fig. 2) may have had a role in the initiation and evolution of the Cheyenne storm. Cheyenne lies in the flat valley of Crow Creek, which flows generally east-southeast across southern sections of the city. Dry Creek, a tributary of Crow Creek, also has its headwaters west-northwest of Cheyenne. It flows through northern sections of Cheyenne before joining Crow Creek a few miles east of the city.

The Cheyenne Ridge lies about 10 km south of the city and rises 60-100 m higher than the elevation of the city. The ridge line is oriented west-northwest to east-southeast. South of the ridge line, the terrain slopes downward to the southeast, dropping about 300 m within 50 km. The slope is for the most part gradual except for the Chalk Bluffs region about 25 km south-southeast of Cheyenne where elevation abruptly drops 60-100 m. Air parcels being transported by southeasterly low-level winds will not only be lifted by the terrain as they approach the Cheyenne Ridge line, but may also be channeled westward by the Chalk Bluffs to converge into the area along the state line south-southwest of Cheyenne.

3. THE LARGER SCALE ENVIRONMENT 12 HOURS BEFORE THE STORM

A mass of cool air was spreading southward over the northern and central Great Plains and the upper Mississippi Valley. At 1200 GMT, 1 August 1985, the leading edge of the cooler air had reached southern Missouri, northern Oklahoma, and the Texas panhandle, and had spread westward over the high Plains to reach the foothills of the central Rocky Mountains. A nearly stationary front, marking the western edge of this cooler air, stretched from near Casper and Laramie, WY, south to Denver, CO, and the Texas panhandle, where it turned eastward into northern Oklahoma. The lower stratus clouds and fog are clearly evident on the 1631 GMT satellite image (Fig. 3) stretching from the Texas panhandle northwest into eastern Montana. Note the jagged appearance of the low cloudiness over the high Plains. Apparently, moist air returning northward over the high Plains was being lifted by the terrain, forming low stratus and fog mainly over the upstream slopes of the east-west ridges. The Cheyenne Ridge was still covered by low clouds, while the South Platte River Valley to the south was clear and warming up. Note the solid low overcast extending from the Nebraska panhandle southeast across northeastern Colorado and western Kansas. This cloudiness persisted and kept these

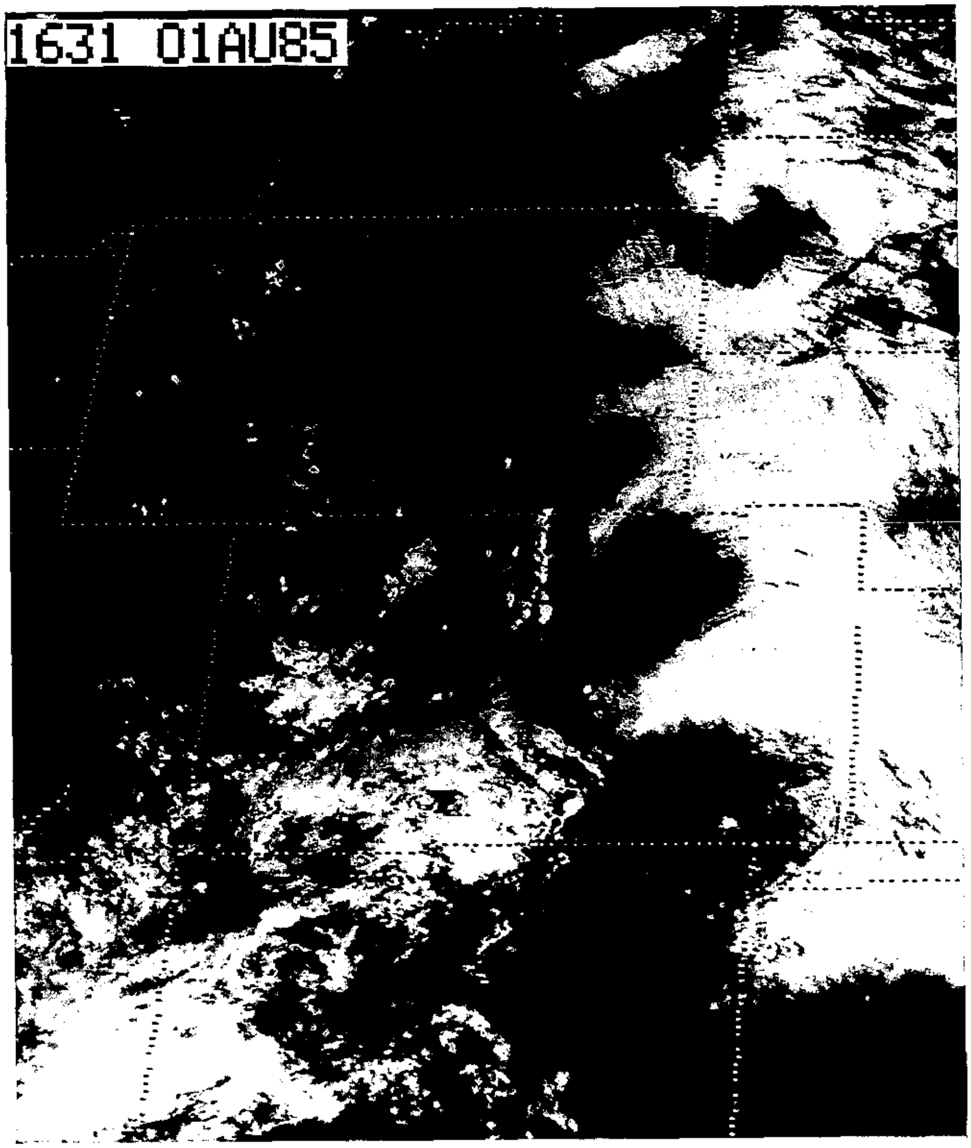


Figure 3. GOES-West visible (1-km-resolution) image for 1631 GMT, 1 August 1985.

areas cool during the day, contributing to the strengthening of the low-level southeasterly flow over eastern Colorado by late afternoon. A cyclonic vorticity-convergence zone had formed in the Denver region during the morning hours. This mesoscale low-pressure area and circulation feature frequently occurs under conditions of post-frontal southeasterly flow. The development of the cyclonic vorticity-convergence zone appears to have been topographically forced by the interaction of low-level southeasterly flow with the east-west ridge of higher terrain south of Denver and the north-south foothills (Szoke et al., 1984).

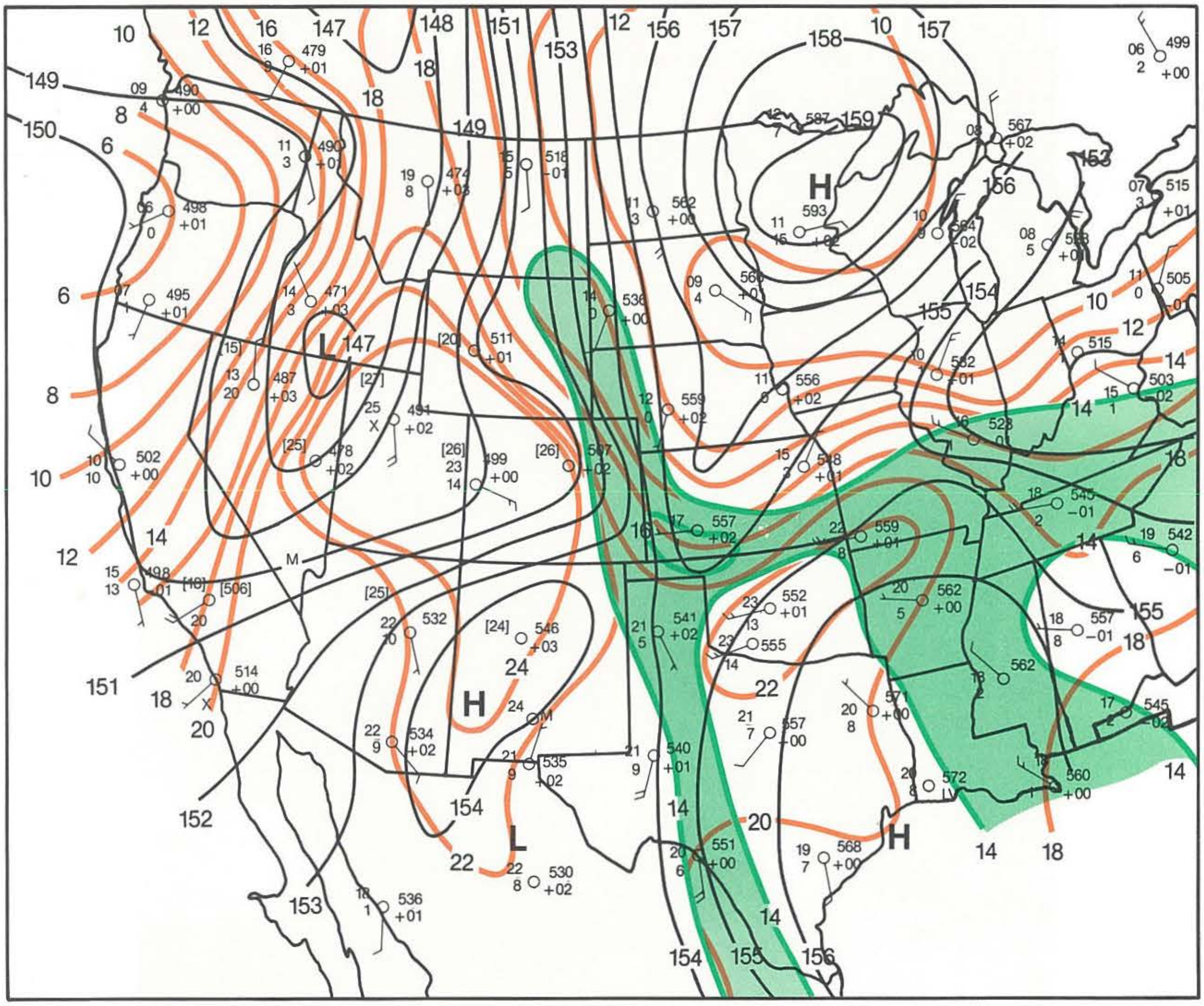


Figure 4. 850-mb analysis for 1200 GMT, 1 August 1985. Height contours (dam) and station plots are in black. Green-shaded area indicates dewpoint temperature ≥14°C. Orange lines represent isotherms (°C).

The 850-mb chart for 1200 GMT illustrates some important features (Fig. 4). The leading edge of cooler air extends from western Montana south to a weak low-pressure center over southern Idaho, continuing southwest to southern California. The nearly stationary front along and near the foothills of Wyoming and Colorado is indicated by the strong thermal gradient over that area. A narrow tongue of moist air (dewpoint temperatures of 14°-16°C) is flowing north and northwestward over the central high Plains, covering most of eastern Colorado and extreme eastern Wyoming.

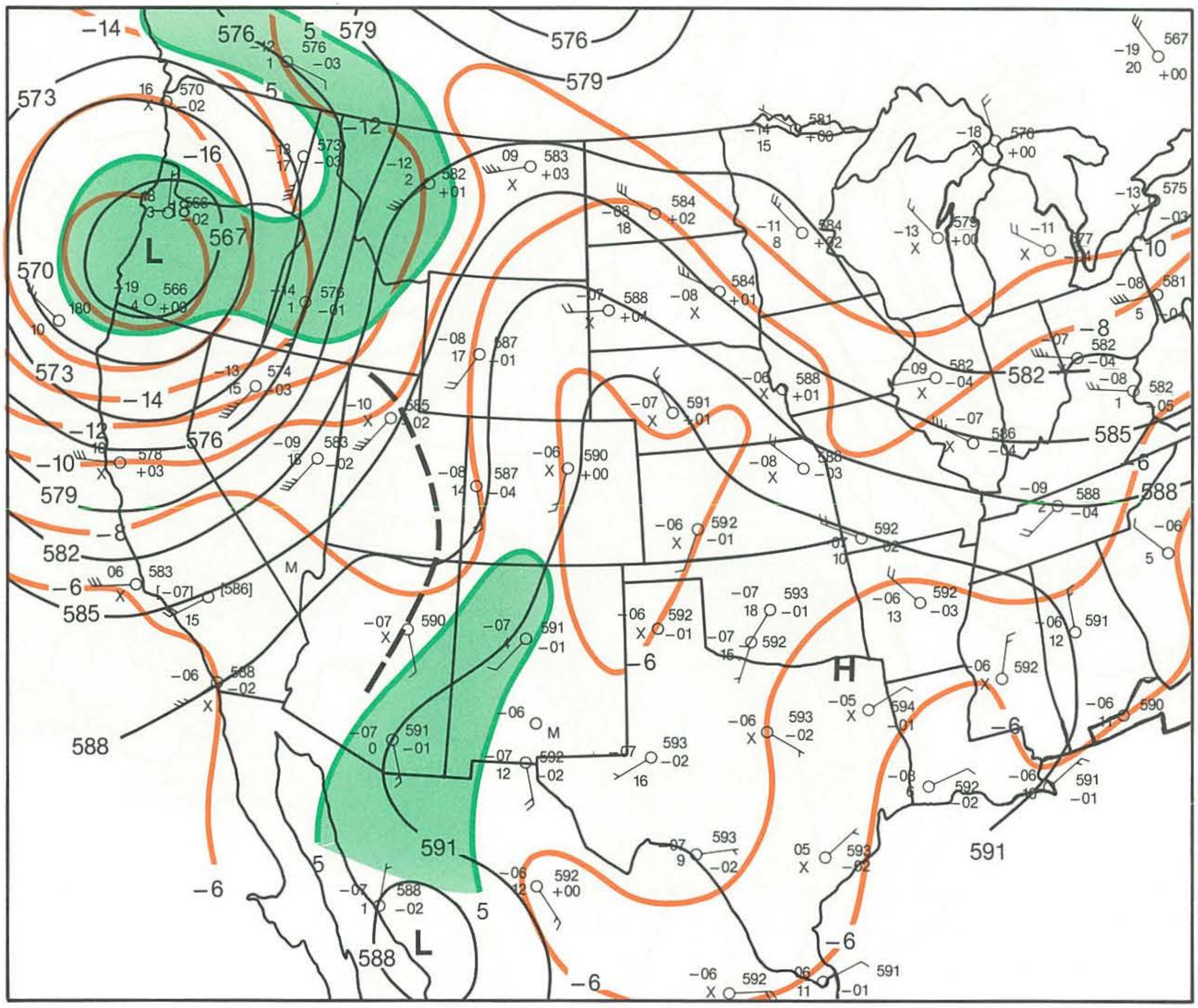


Figure 5. 500-mb analysis for 1200 GMT, 1 August 1985. Height contours (dam) and station plots are in black. Green shaded area indicates dewpoint depression ≤5°C. Orange lines represent isotherms (°C). The black dashed line marks position of the short-wave trough.

At 1200 GMT a ridge at 500 mb (Fig. 5) extended from central Oklahoma northwestward across the Nebraska panhandle to eastern Montana. (Negatively tilted ridges were also observed over the Plains during the 1972 Rapid City flash flood and the 1976 Big Thompson flash flood.) A cold low had moved onto the Oregon coast with a trough extending south into California. A weak short wave, evident over eastern Utah, was moving northeastward ahead of the main trough. This short wave is indicated by the

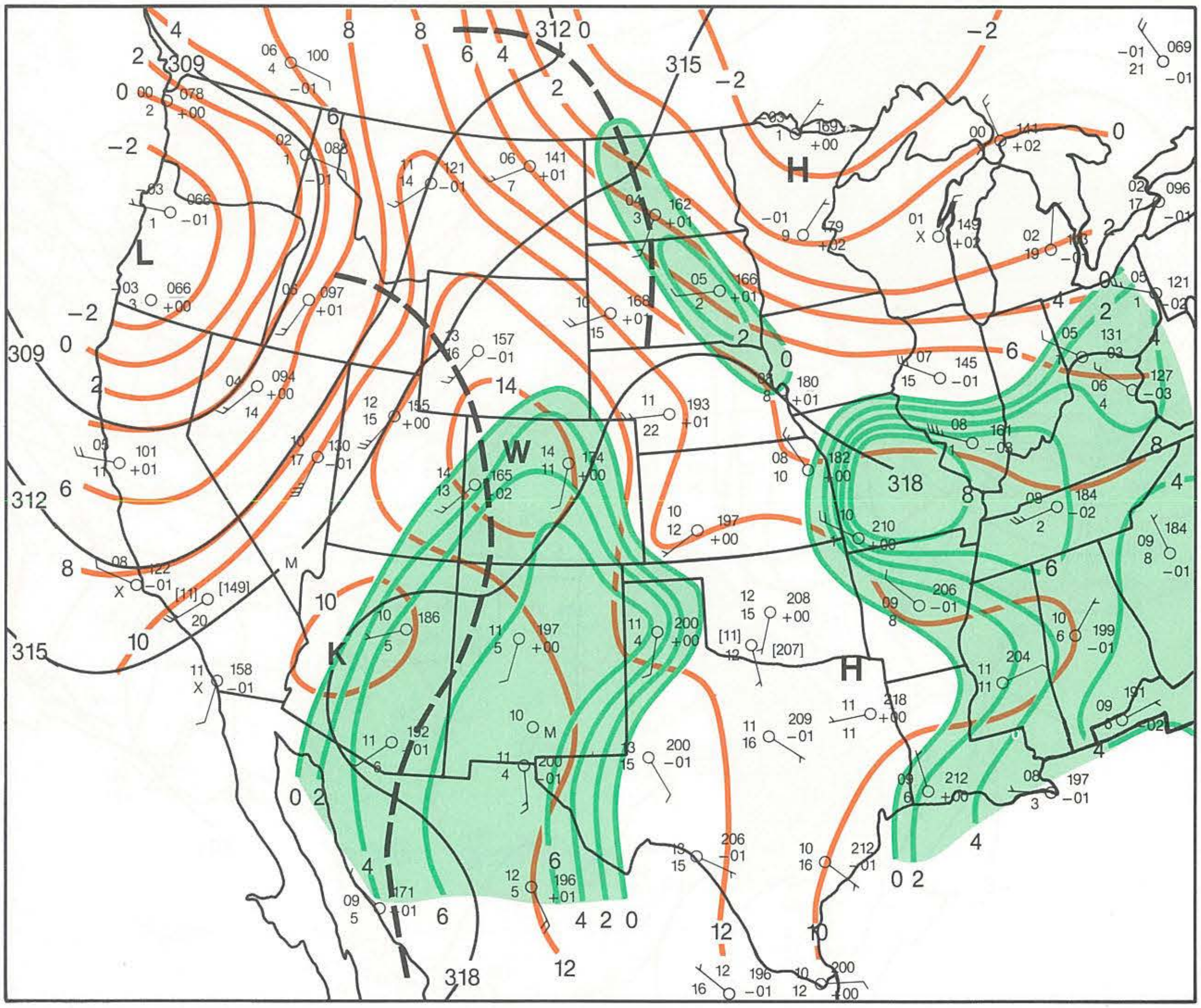


Figure 6. 700-mb analysis for 1200 GMT, 1 August 1985. Height contours (dam) and station plots are in black. Green-shaded area indicates dewpoint temperature ≥0°C. Orange lines represent isotherms (°C). The black dashed line marks position of the short-wave trough.

500-mb-height fall at Grand Junction, CO, and the thermal trough extending from northwestern Utah to the Four Corners area.

Another interesting feature, evident on the 1631 GMT satellite image (Fig. 3) and the 1200 GMT 700-mb (Fig. 6) and 500-mb (Fig. 5) charts, is the anticyclonically curving tongue of southwest monsoon moisture moving northward into the central Rockies. This tongue of moisture extended from southern and eastern Arizona and western New Mexico into southwestern and north central Colorado to extreme southeastern Wyoming.

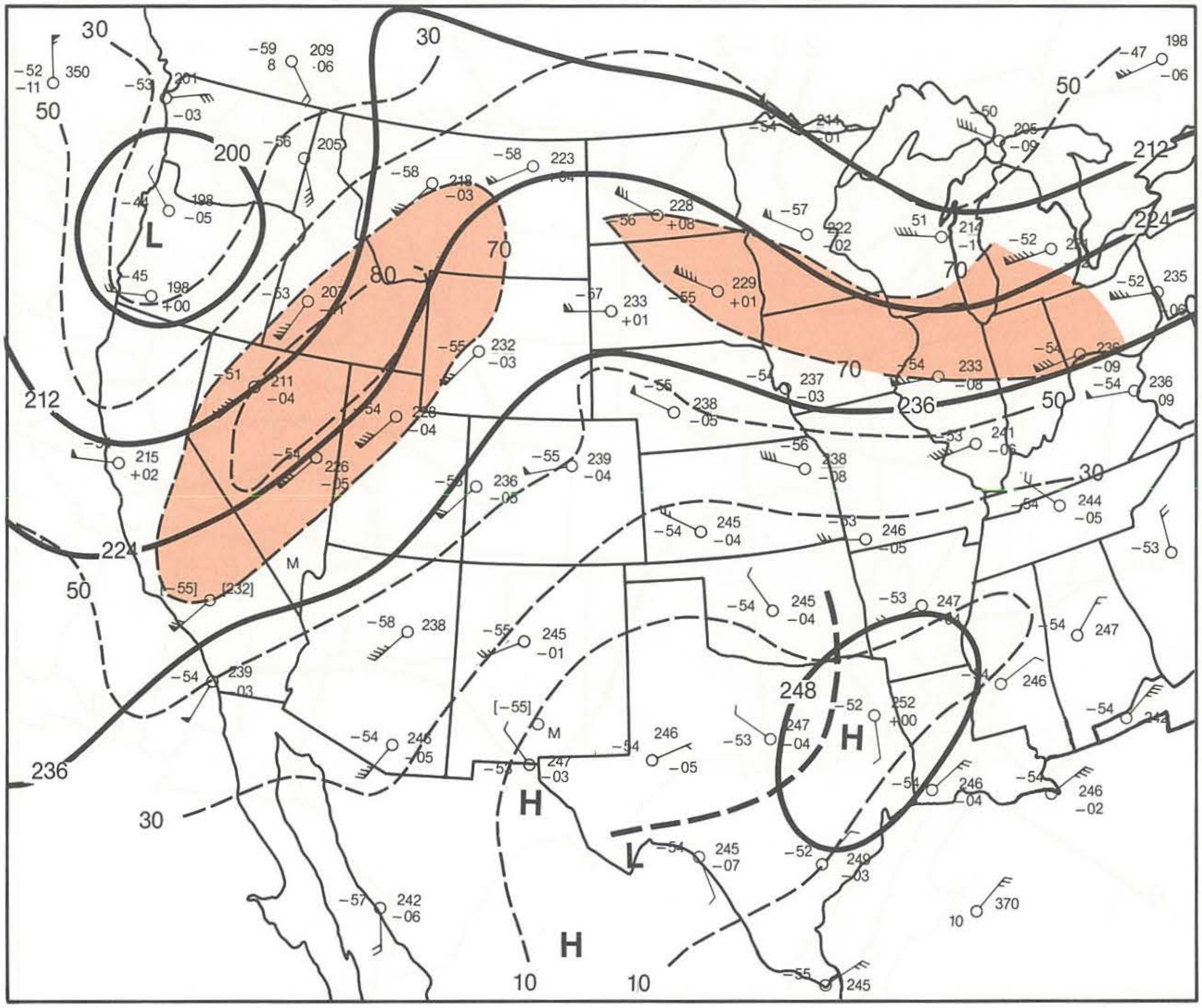


Figure 7. 200-mb analysis for 1200 GMT, 1 August 1985. Height contours (solid), isotachs (dashed) and station plots are in black. Heights are in dekameters (leading 1 is omitted; for example, 236 = 12360 m). Wind speeds are in knots; speeds ≥70 kt are shaded orange.

A warm thermal ridge at 700 mb extended from a warm pool over northwest Colorado, northwest across western Wyoming to central Montana. The air was cooler and moist at 700 mb over Arizona and New Mexico and was spreading northward in the southwest monsoon flow.

Three different air masses were evident in the middle troposphere over the western United States: (1) the drier, cooler, and more stable air mass behind the Pacific front associated with the West Coast trough; (2) the moist southwest monsoon air mass with

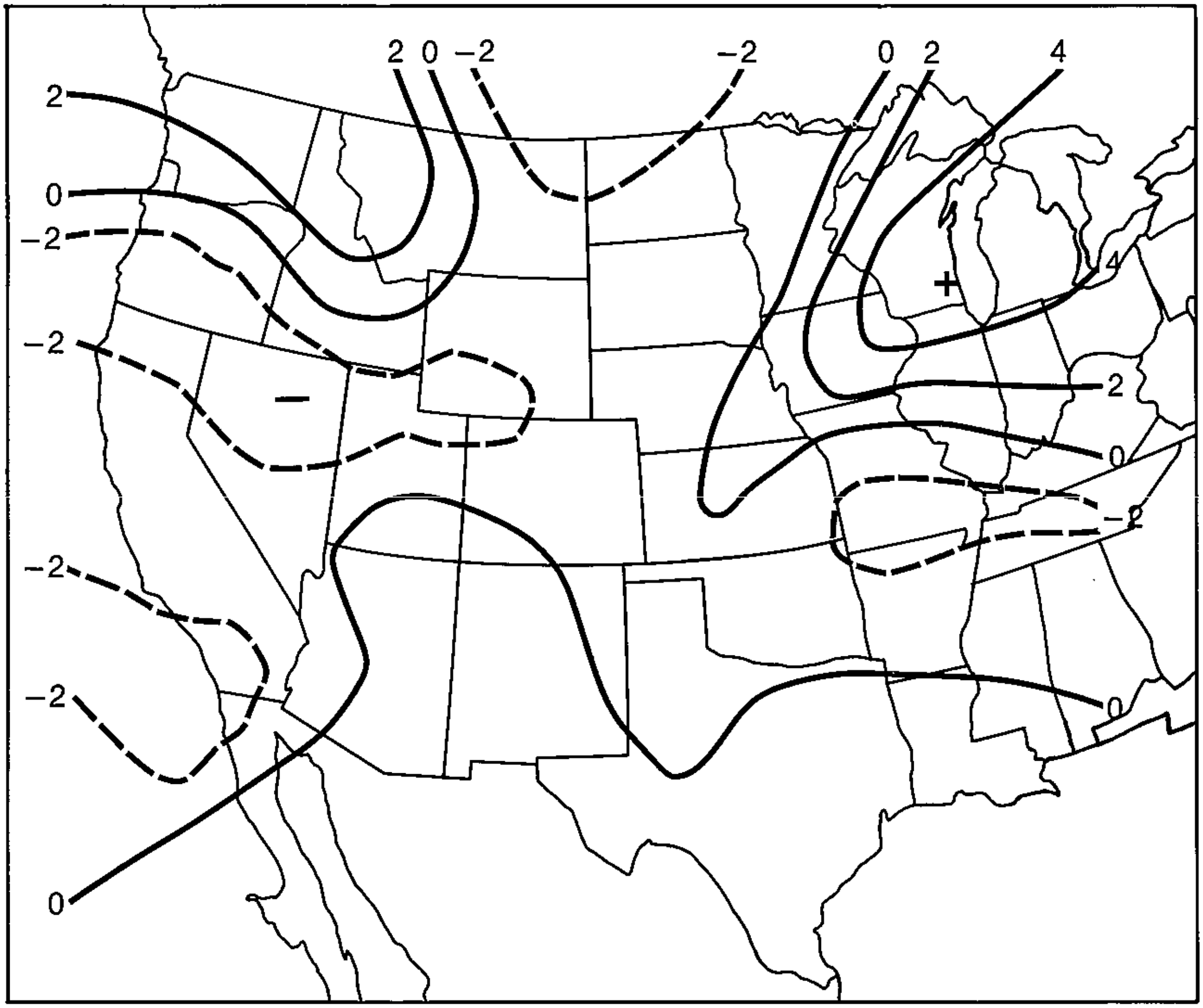


Figure 8. 600-mb divergence of Q vectors (10^{-17} s^{-3} mb^{-1}) for 1200 GMT, 1 August 1985. Plus and minus signs mark the locations of the positive and negative maximum values.

lapse rates near the moist adiabatic value; and (3) an unstable air mass over the northern Rockies associated with a deep mixed layer and lifting ahead of the West Coast trough.

The 200-mb chart at 1200 GMT (Fig. 7) shows a warm-core low center over western Oregon with a trough extending south off the southern California coast. A band of high winds extends from southern California northeast to eastern Montana. A jet maximum (50 m s^{-1}) is located over the northeast corner of Nevada. The downstream ridge extends over the high Plains from eastern Montana south into western Texas. The wind field at 200 mb over northern Colorado and southeastern Wyoming shows anticyclonic

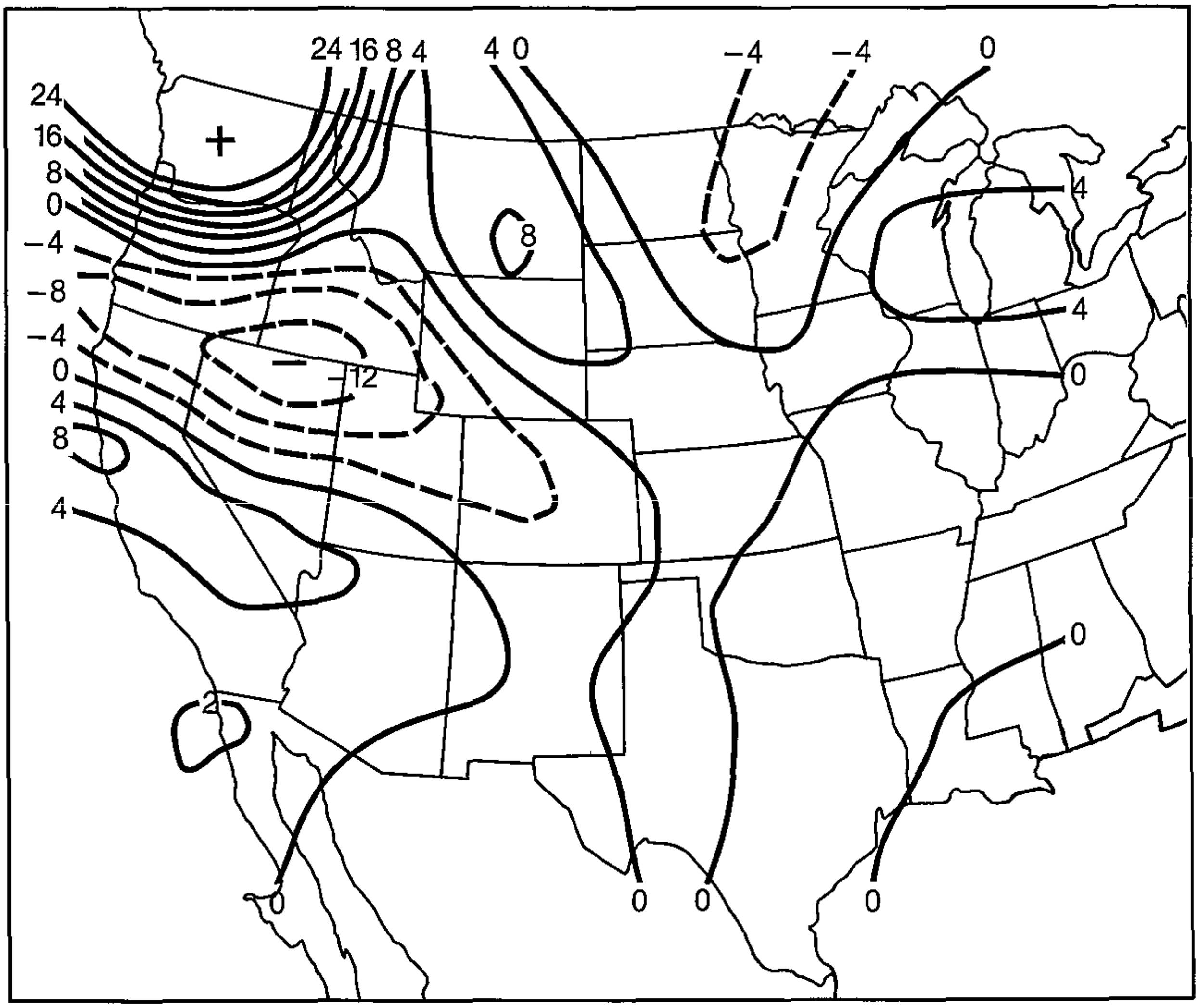


Figure 9. 400-mb divergence of Q vectors (10^{-17} s^{-3} mb^{-1}) for 1200 GMT, 1 August 1985. Plus and minus signs mark the locations of positive and negative maximum values.

curvature and shear as well as moderate difluence. Falling height tendencies, centered near Boise, ID, suggest that the jet maximum over northeastern Nevada will move northeastward as the jet stream in which it is embedded translates eastward with time.

The configuration and strength of the large-scale geostrophic forcing as measured by the divergence of Q (Hoskins, 1975; Barnes, 1985) is shown in Fig. 8 for the lower troposphere and in Fig. 9 for the upper troposphere. Quasi-geostrophic forcing requires upward motion in the area of converging Q vectors extending from northwestern Colorado to southwestern Idaho to maintain geostrophic and hydrostatic balance.

4. METEOROLOGOCAL DEVELOPMENTS DURING THE AFTERNOON

The 1800 GMT surface chart (Fig. 10) shows a quasi-stationary front extending from near Casper, WY, southeast between Laramie and Cheyenne, to the vicinity of Denver, and continuing into southeastern Colorado. A weak pressure-fall center is noted over northwestern Colorado. Lifting of the moist, low-level flow by the east-west ridges

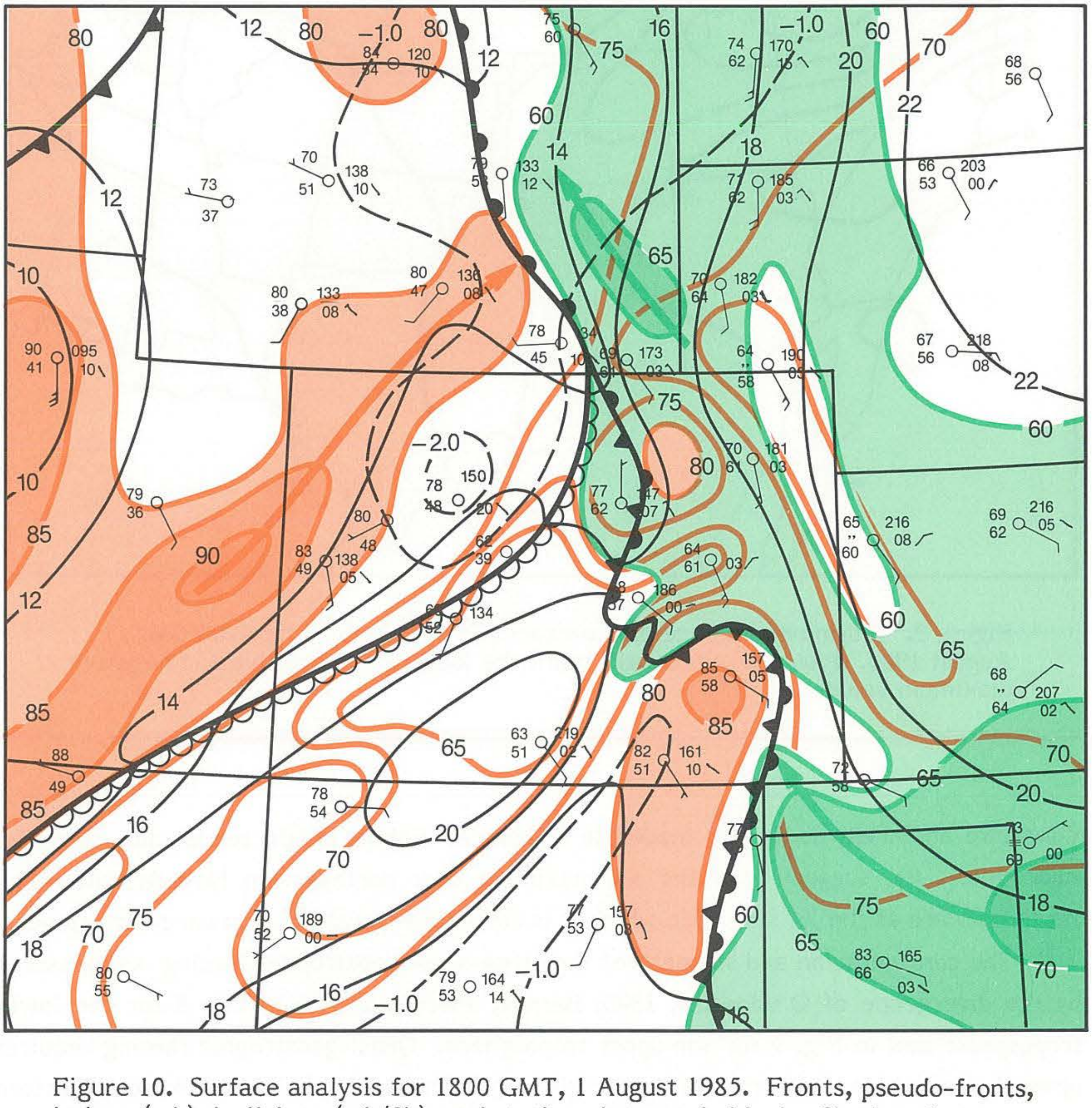


Figure 10. Surface analysis for 1800 GMT, 1 August 1985. Fronts, pseudo-fronts, isobars (mb), isallobars (mb/3h), and station plots are in black. Shades of orange represent areas of temperature ≥80°F. Shades of green represent areas of dewpoint temperature ≥60°F.

continued to produce mesoscale regions of low clouds and fog (Fig. 11). While low stratus continued to cover the southeastern slope of the Palmer Ridge south of Denver, cloudiness was dissipating over the Cheyenne Ridge. The 1800 GMT surface chart indicates slow warming of these east-west ridges. In contrast, the Arkansas River and South Platte River Valleys were heating rapidly; temperatures were in the high 70s and low 80s (°F). A feature of interest on the 1800 GMT surface chart and 1801 GMT satellite image is the continuous band of stratus extending from southwestern Kansas to the Nebraska panhandle. Temperatures remained near or below 65°F in this band; fog and drizzle were reported.

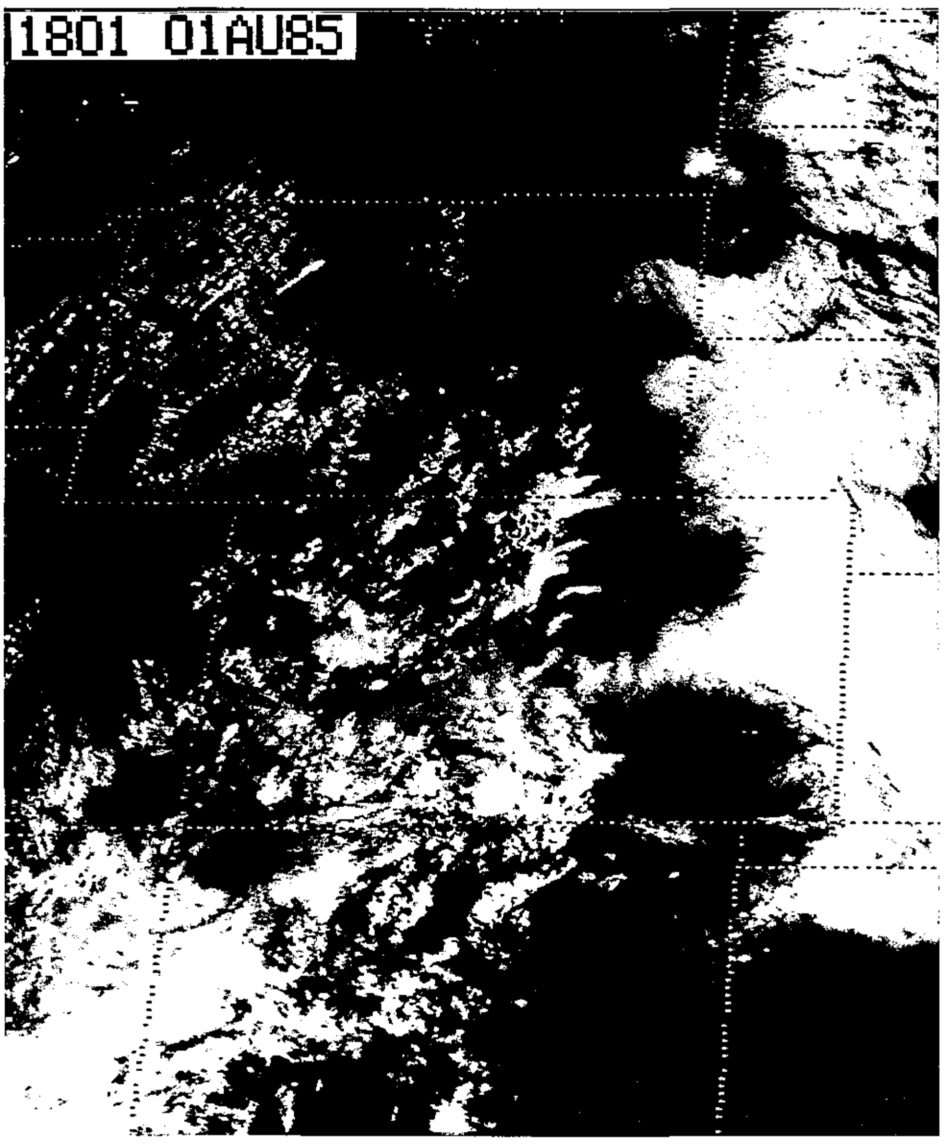


Figure 11. GOES-West visible (1-km-resolution) image for 1801 GMT, 1 August 1985.

Another feature of interest on the 1800 GMT surface chart and 1801 GMT satellite image is the demarcation zone between a hot, dry, and deeply mixed air mass over the intermountain area and the cooler, more moist, monsoon air spreading slowly northward over central and eastern Colorado and southeastern Wyoming. This boundary lay between Laramie and Cheyenne at the surface; cumulonimbus formation and rain showers were already occurring southeast of Laramie and just west of Cheyenne. Anvil cirrus streaming east-northeastward from this activity toward Cheyenne is evident on the satellite image. The public reported a funnel cloud 40 miles west of Cheyenne at 1825 GMT, associated with this activity. Convective activity was also developing over the eastern foothills of the central Rockies of northern New Mexico and Colorado.

The dry/moist interface is also quite apparent in the 6.7-μm water vapor channel image from 1900 GMT (Fig. 12). The darker gray shades indicate very dry conditions in the middle and upper troposphere in a zone arcing from central Utah northeastward

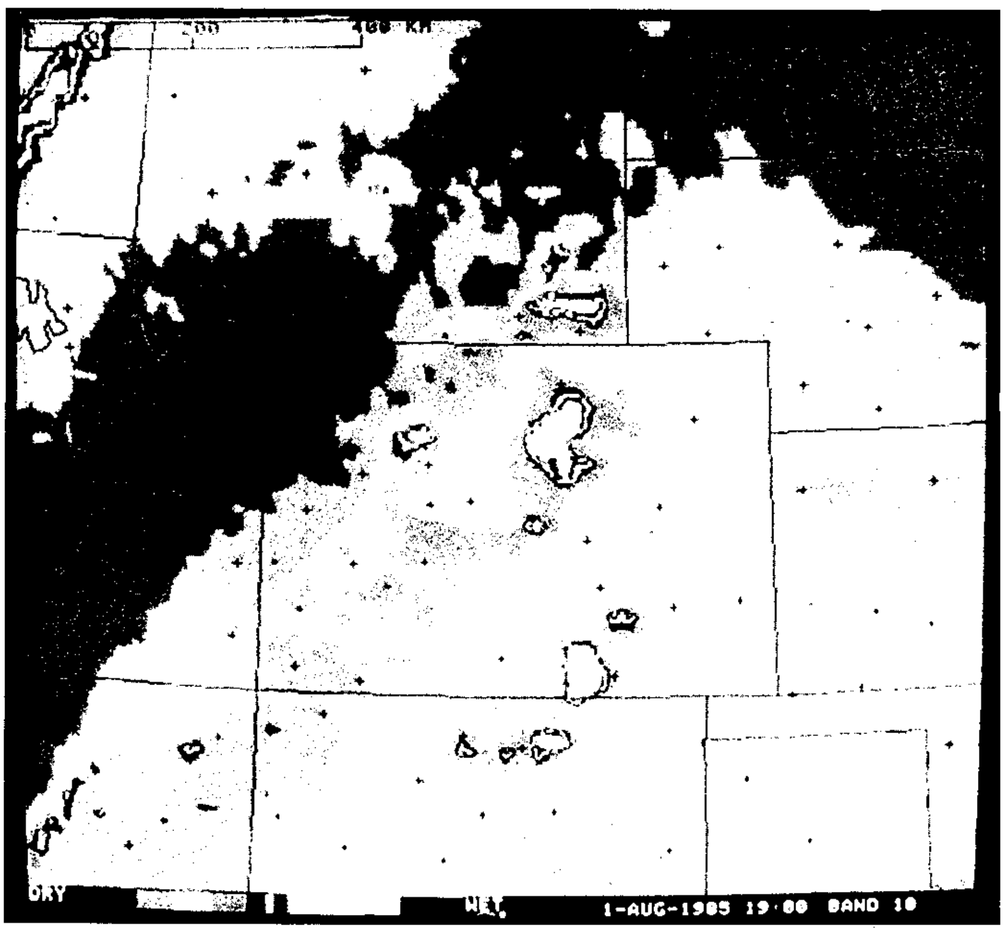


Figure 12. GOES 6.7-μm water vapor channel image for 1900 GMT, 1 August 1985.

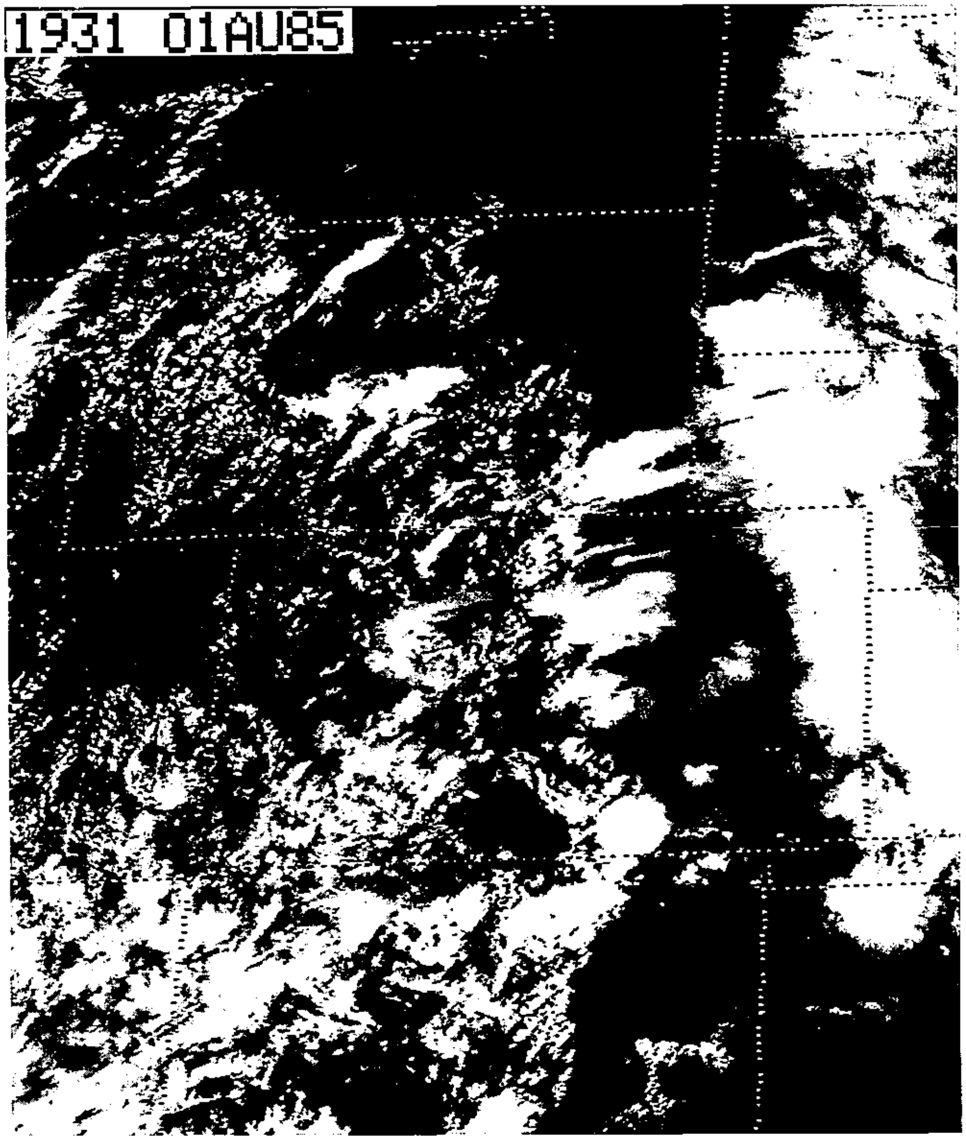


Figure 13. GOES-West visible (1-km-resolution) image for 1931 GMT, 1 August 1985.

through central and eastern Wyoming. Light gray to white shading indicates areas of deep moisture and cloudiness above about 700 mb over most of Colorado, southeastern Wyoming, and adjacent states to the east and south.

The 1931 GMT satellite image (Fig. 13) shows continued thunderstorm development from southeastern Wyoming south along the foothills of Colorado and New Mexico. Low clouds linger, but have thinned, on the Palmer Ridge southeast of Denver, while low clouds appear to have dissipated on the Cheyenne Ridge. An impressive thunderstorm

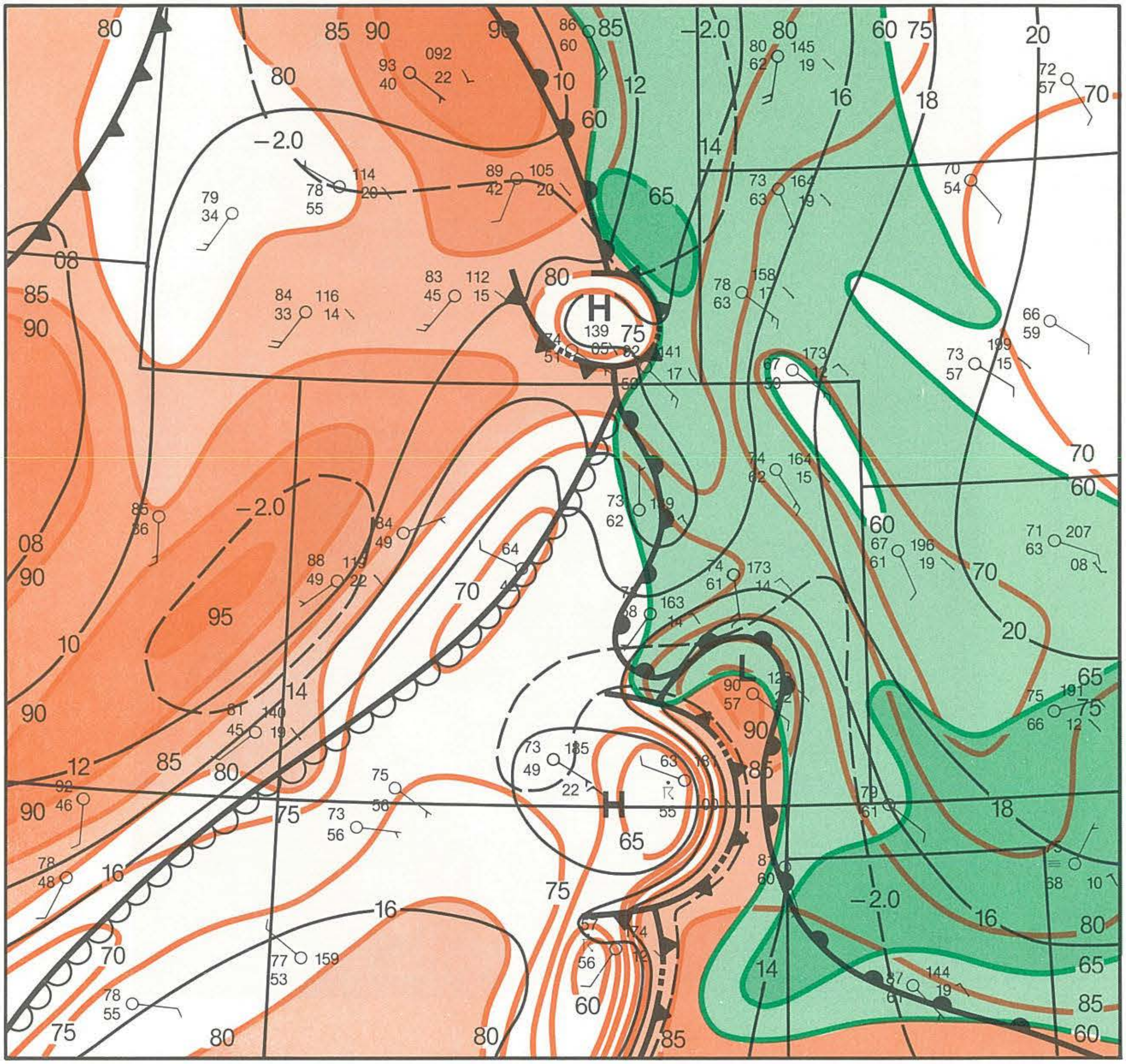


Figure 14. Surface analysis for 2100 GMT 1 August 1985. Fronts, pseudo-fronts, isobars (mb), isallobars (mb/3h), and station plots are in black. Shades of orange represent areas of temperature ≥80°F. Shades of green represent areas of dewpoint temperature ≥60°F.

system is visible about 45 km northwest of Cheyenne. Radar observations of this storm from Cheyenne at 1907 GMT indicated maximum tops of 16.5 km msl.

The 2100 GMT surface chart (Fig. 14) and the 2101 GMT satellite image (Fig. 15) indicate widespread convection from southeastern Wyoming south along the foothills and adjacent high plains of Colorado and New Mexico, about 3 h before the Cheyenne storm. A squall line has developed from near Pueblo, CO, south into northeastern New Mexico,

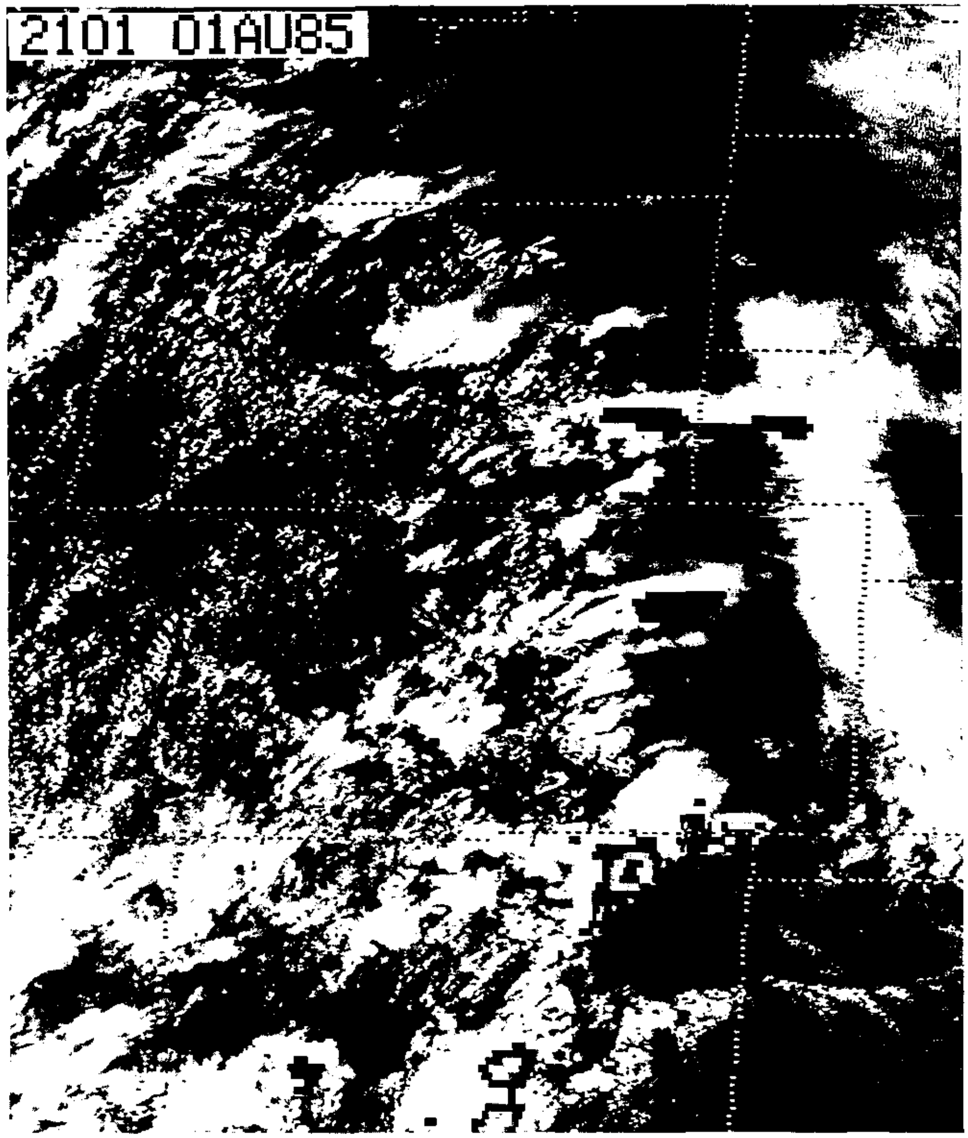


Figure 15. GOES-West visible/enhanced-infrared combination image for 2101 GMT, 1 August 1985. Infrared equivalent black body temperatures colder than -54°C are enhanced dark gray.

and mesoscale high-pressure centers have developed behind this line. Farther north, thunderstorms continue to develop north, west, and southwest of Cheyenne. The 2100 GMT surface chart shows evidence of a growing mesoscale high-pressure center beneath an intensifying thunderstorm system just north and northwest of Cheyenne. Outflow from this system and the earlier thunderstorm activity northwest of Cheyenne has spilled westward into Laramie, where surface winds have shifted from westerly at 1800 GMT to east-southeasterly at 2100 GMT and temperatures have dropped to 74°F. The outflow

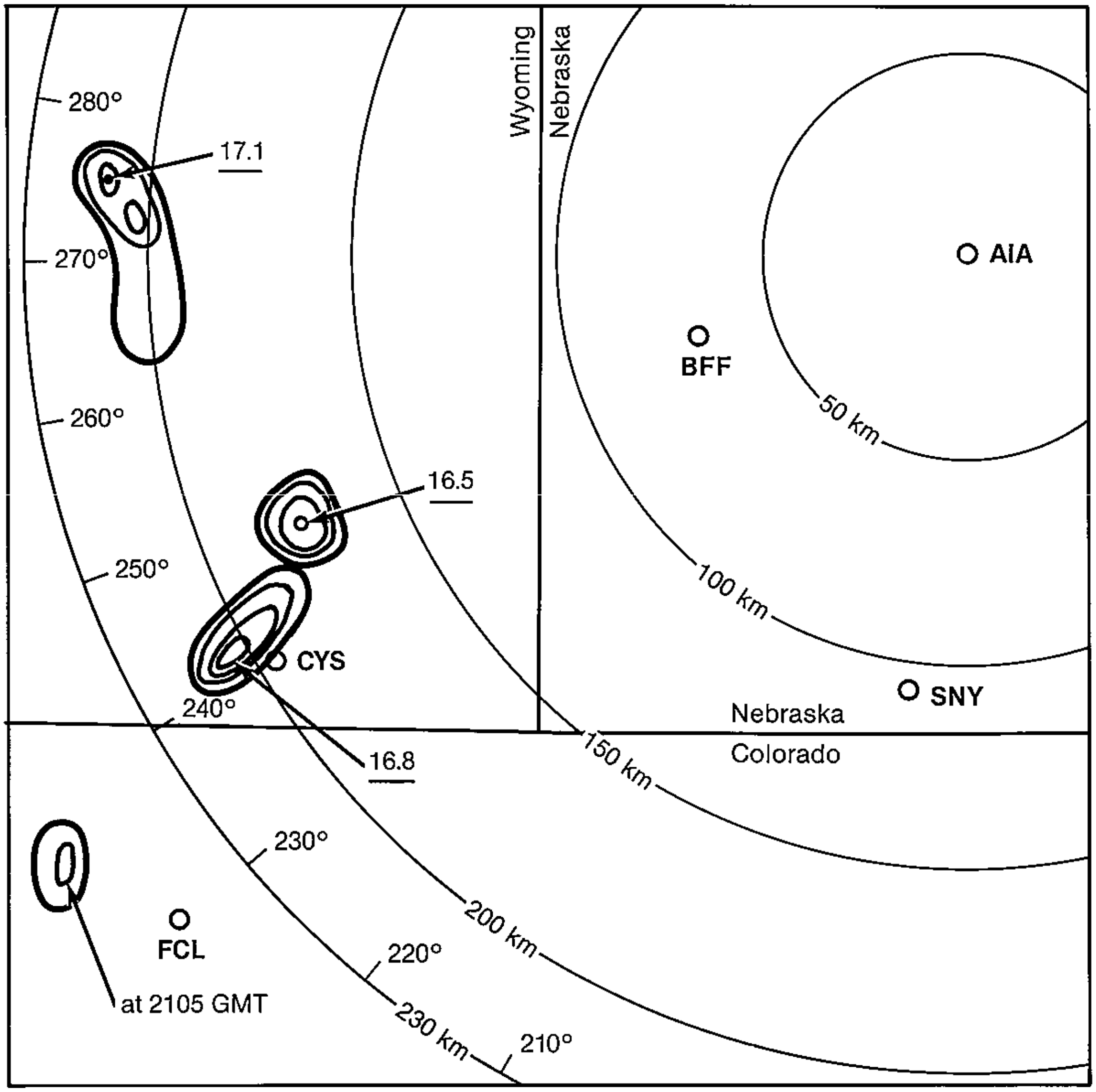


Figure 16. Radar reflectivities from Alliance, NE, WSR-57 at 2100 GMT, 1 August 1985. Echo top heights are in kilometers. From the outside of the echo, contours are 0-29, 30-40, 41-45, 46-49, and 50-56 dBZ.

boundary is still north of the Cheyenne WSFO, as evidenced by the warm 82°F temperature and southerly wind at that site. Radar observations from Alliance, NE, at 2100 GMT (Fig. 16) and the 2101 GMT satellite image show two thunderstorm systems developing just north and west of Cheyenne with tops at 16.5 km msl and 16.8 km msl respectively. The two systems were moving slowly northeastward. A funnel cloud associated with this activity was reported at 2110 GMT 22 km north of Cheyenne. Thunder was heard, but no rain fell at the WSFO from these storm cells.

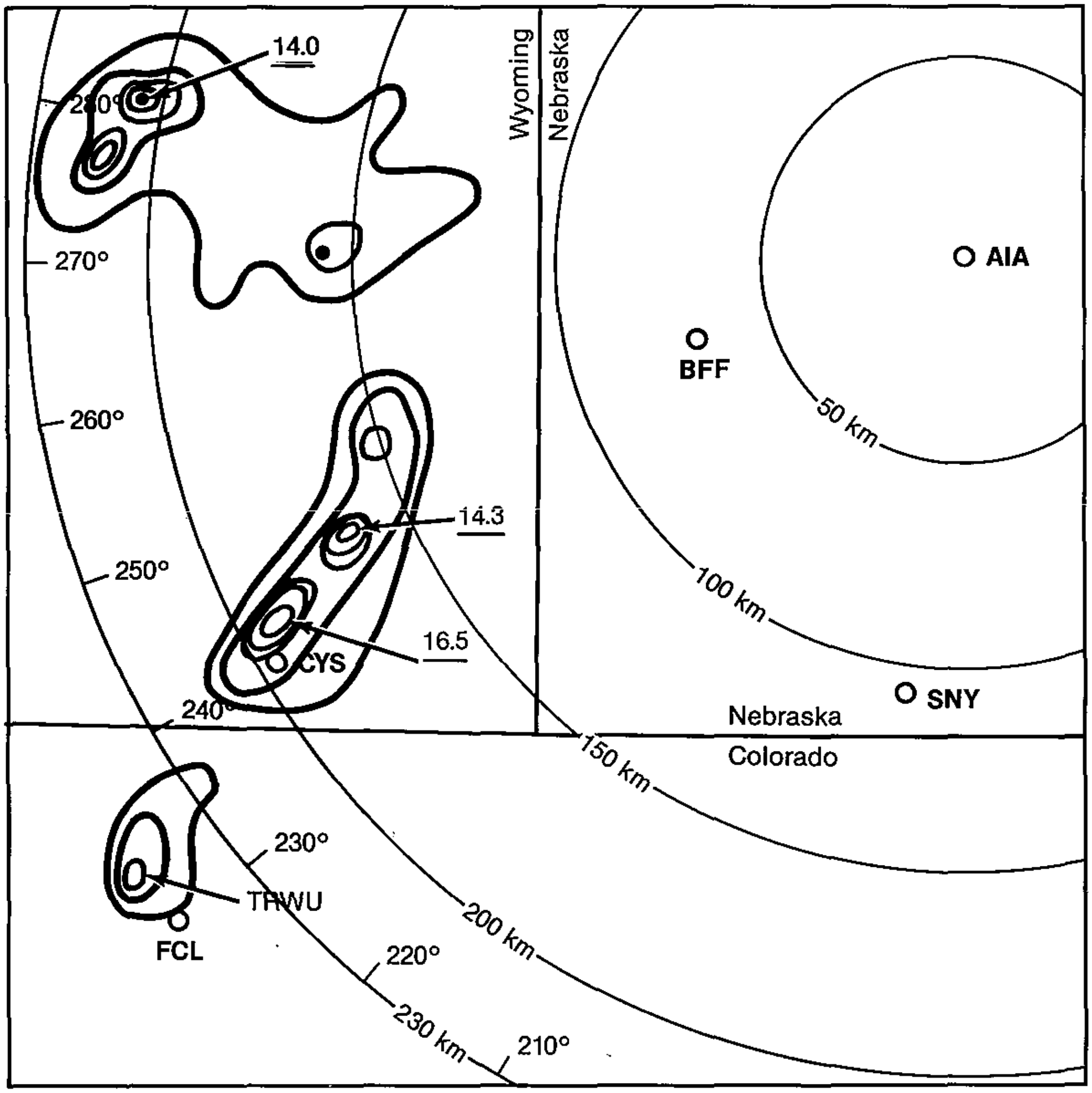


Figure 17. Radar reflectivities from Alliance, NE, WSR-57 at 2125 GMT, 1 August 1985. Echo top heights are in kilometers. From the outside of the echo, contours are 0-29, 30-40, 41-45, 46-49, and 50-56 dBZ.

The arc of thunderstorms lying mainly north of Cheyenne is clearly depicted by the 2125 GMT radar report from Alliance (Fig. 17) and the 2131 GMT satellite image (Fig. 18). This arc configuration of radar echoes suggests the presence of a mesoscale high-pressure center northwest of Cheyenne. New growth southwest of Cheyenne is evident on the satellite image. At 2149 GMT, the wind shifted to northerly at the Cheyenne WSFO and the temperature fell 10°F as cool downdraft air reached the station from the thunderstorm activity passing just to the north.

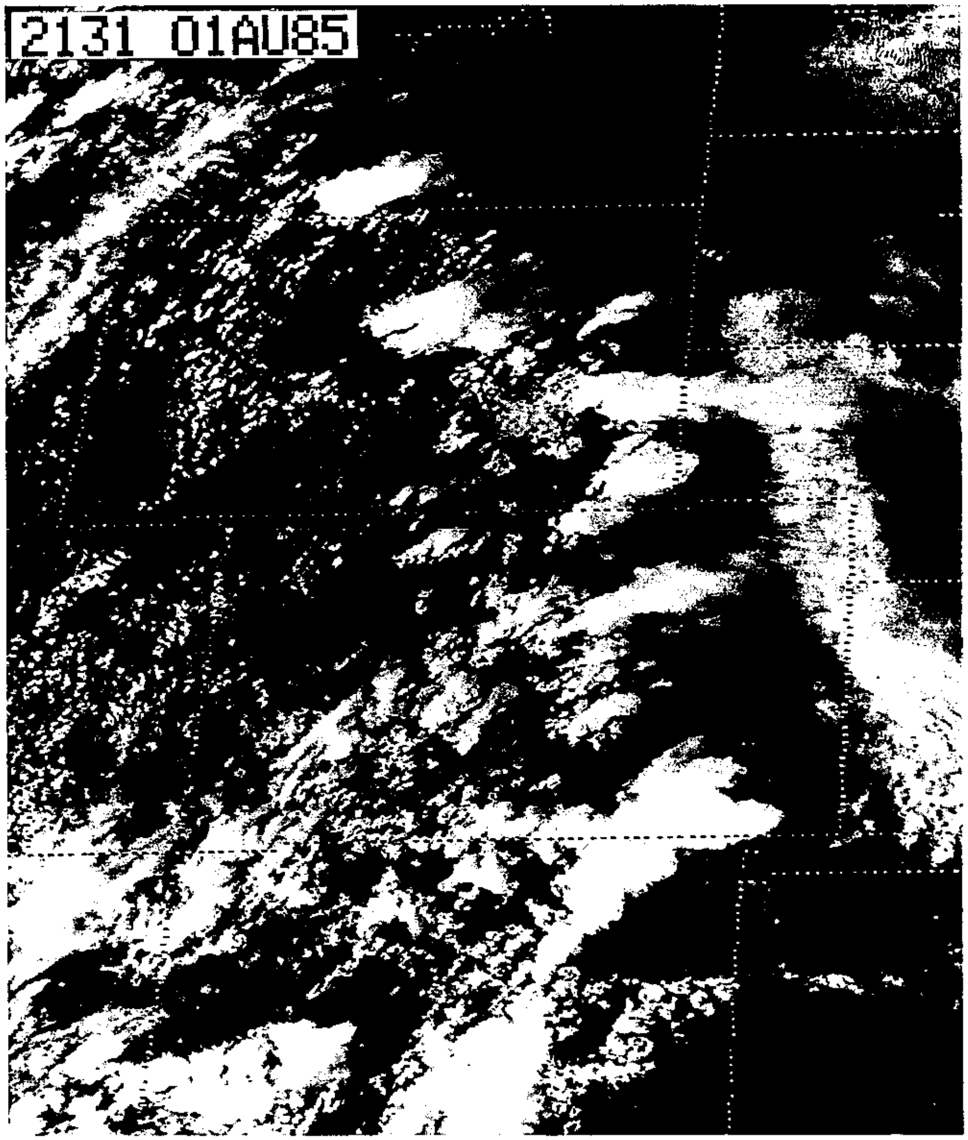


Figure 18. GOES-West visible (1-km-resolution) image, 2131 GMT, 1 August 1985.

At 2223 GMT, the Cheyenne WSFO reported that the thunderstorm activity had moved east of the city; a line of cumulonimbus extended northeast through southeast of the station. The wind was now blowing out of the east-northeast at the WSFO, and cool downdraft air from the storms to the east kept the temperature at 72°F. The line of thunderstorms was clearly observed at 2229 GMT by the Alliance, NE, radar (Fig. 19), which measured a top at 16.8 km msl for the storm a few kilometers east of Cheyenne.

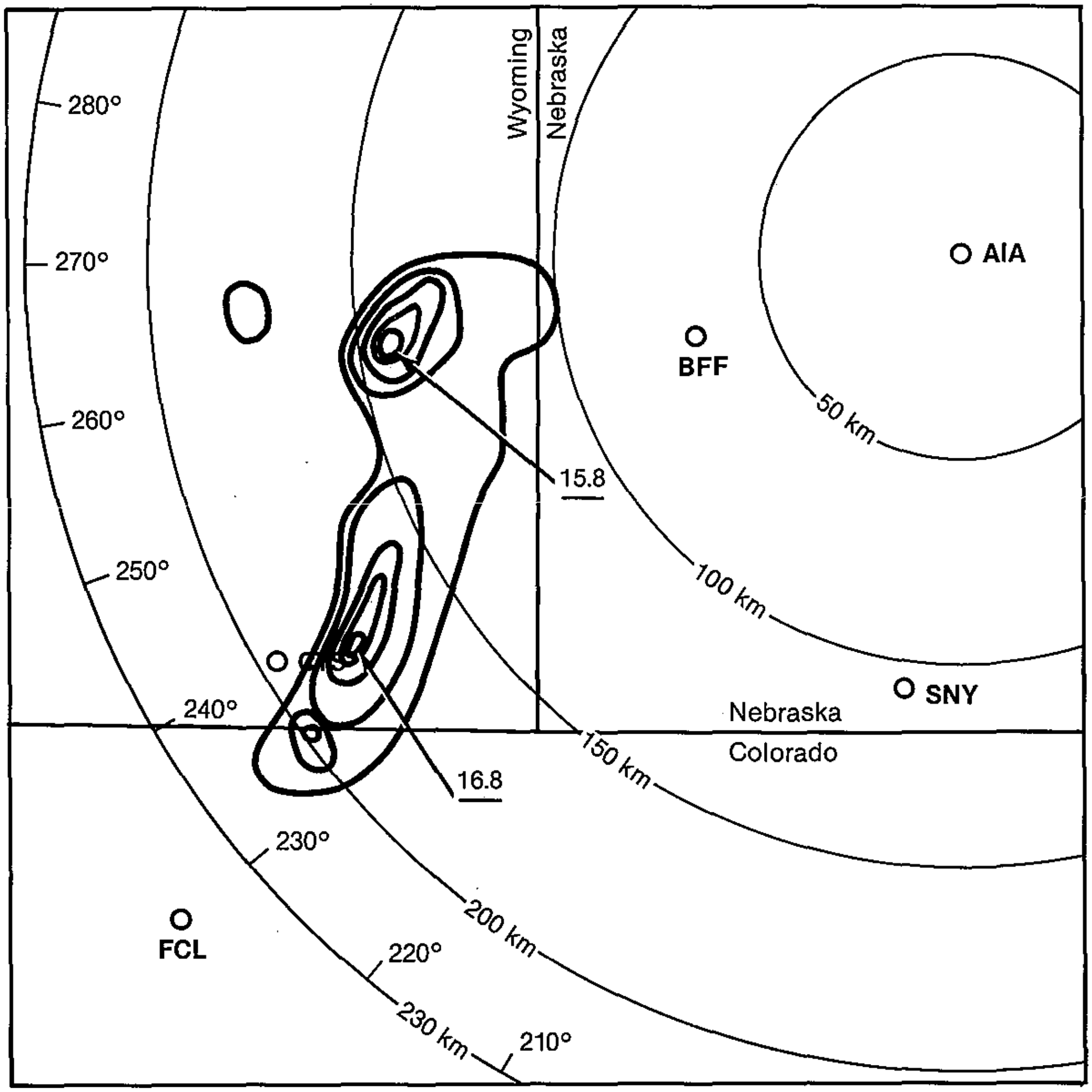


Figure 19. Radar reflectivities from Alliance, NE, WSR-57 at 2229 GMT, 1 August 1985. Echo top heights are in kilometers. From the outside of the echo, contours are 0-29, 30-40, 41-45, 46-49, and 50-56 dBZ.

Several interesting features are present on the 2230 GMT satellite image (Fig. 20). Low clouds and surface temperatures near 70°F continue in a band extending from northwestern Oklahoma across western Kansas into the Nebraska panhandle; the plateau areas of western and south-central Wyoming, northwestern Colorado, and Utah are mostly clear. New tower growth is evident on the southwest end of the thunderstorm line lying to the east and southeast of Cheyenne. A funnel cloud was reported a few kilometers east-southeast of Cheyenne (on Chalk Bluff Road) at 2240 GMT.

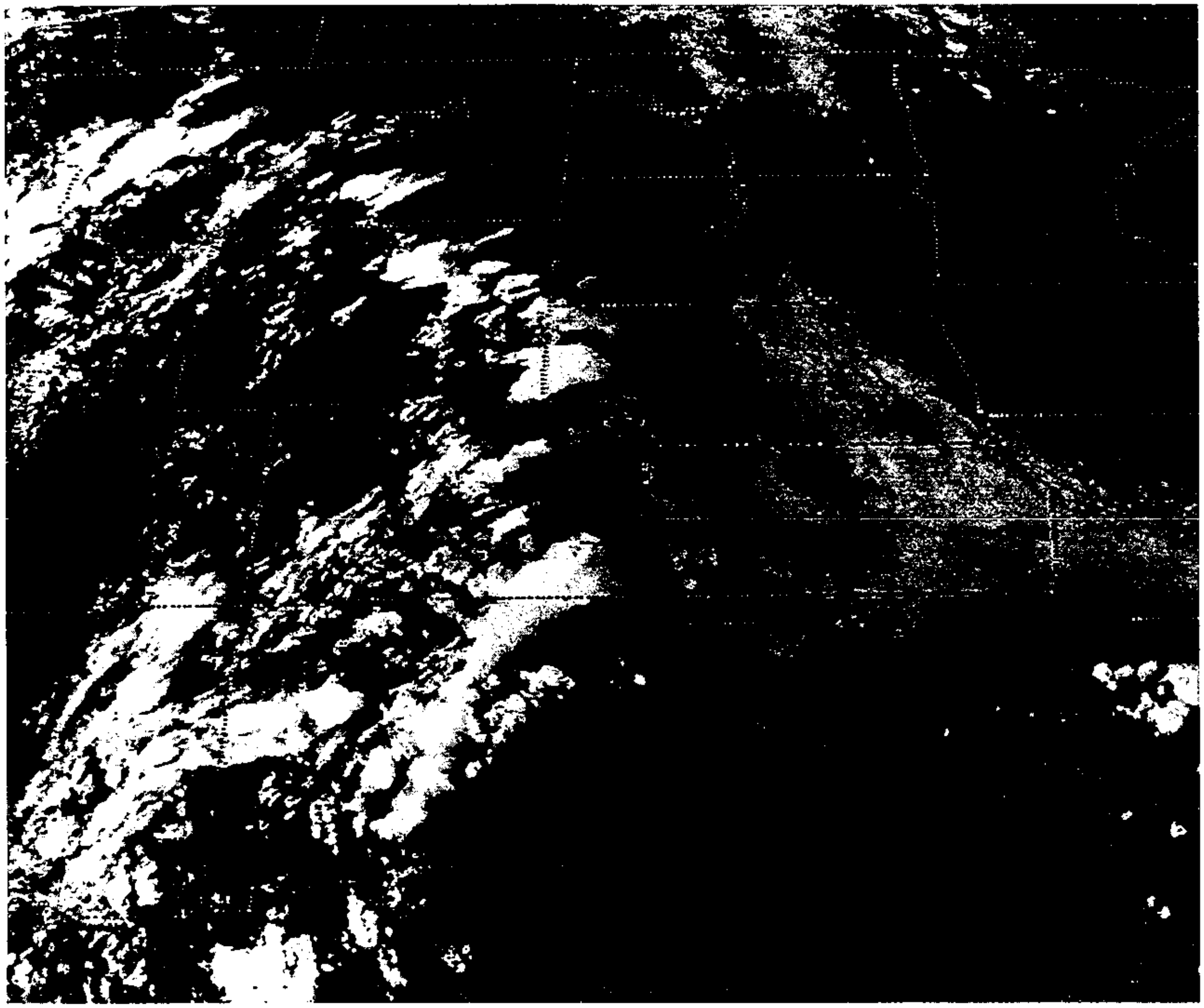


Figure 20. GOES-West visible (2-km-resolution) image for 2230 GMT, 1 August 1985.

Figure 21 shows the surface analysis for 2300 GMT, approximately 1 h before the devastating storm focused on the city of Cheyenne. Note the cool mesoscale high-pressure area over southeastern Wyoming that developed with the earlier thunderstorm activity. The edge of the cool outflow appears to lie nearly stationary just south of Cheyenne, along the elevated terrain of the Cheyenne Ridge (see Fig. 2). (The southward penetration of this cooler air was retarded by the strong ambient southeasterly flow). Hot and dry air persists over most of Utah and extends northeast toward southeastern Wyoming. A southeasterly flow of very moist air extends from southwestern Kansas across east-central Colorado to southeastern Wyoming. The hot and dry southwesterly flow, the moist southeasterly flow, and the cooler easterly flow of downdraft air all converge strongly just west-southwest of Cheyenne.

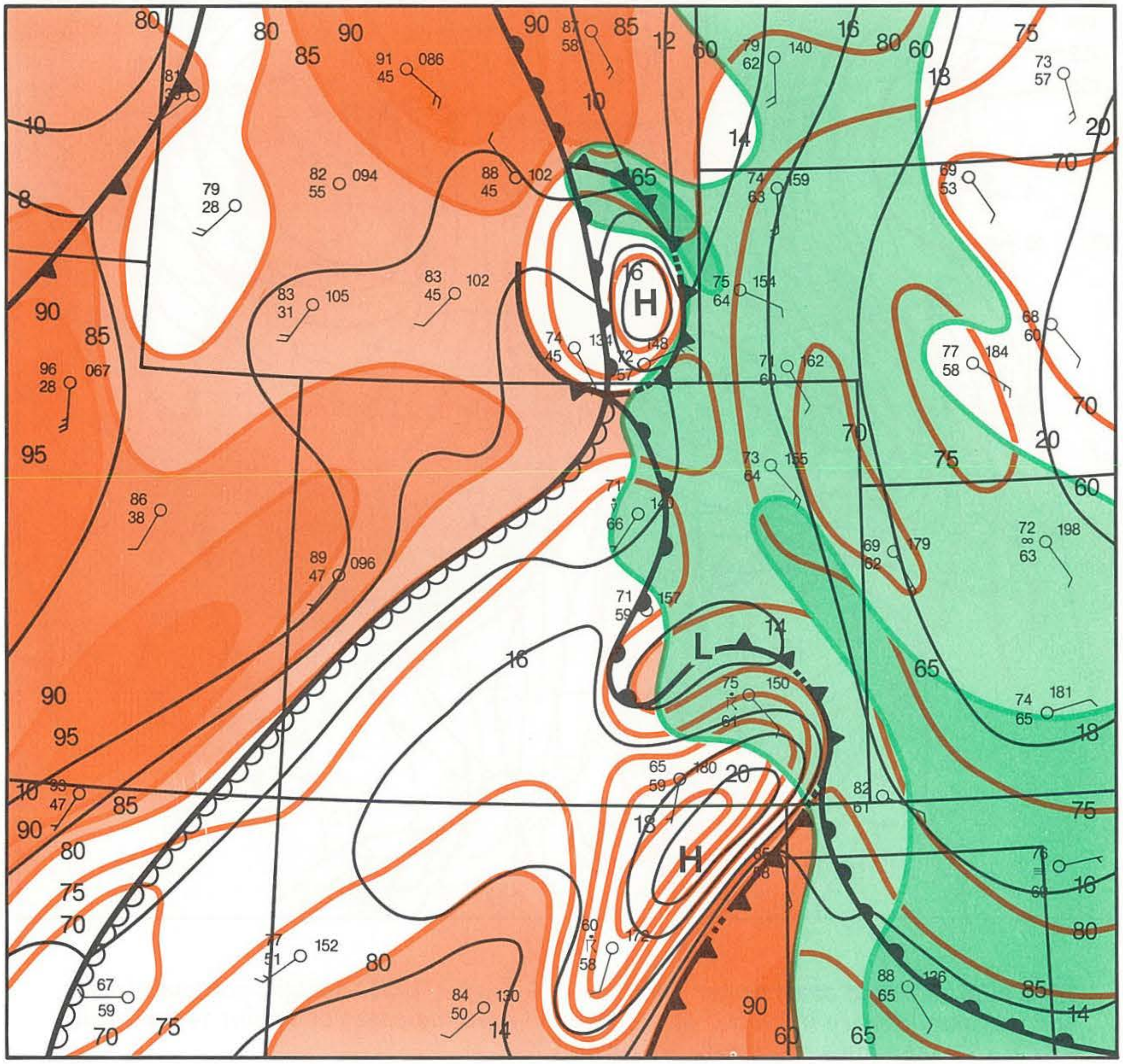


Figure 21. Surface analysis for 2300 GMT, 1 August 1985. Fronts, pseudo-fronts, isobars (mb), isallobars (mb/3h), and station plots are in black. Shades of orange represent areas of temperature ≥80°F. Shades of green represent areas of dewpoint temperature ≥60°F.

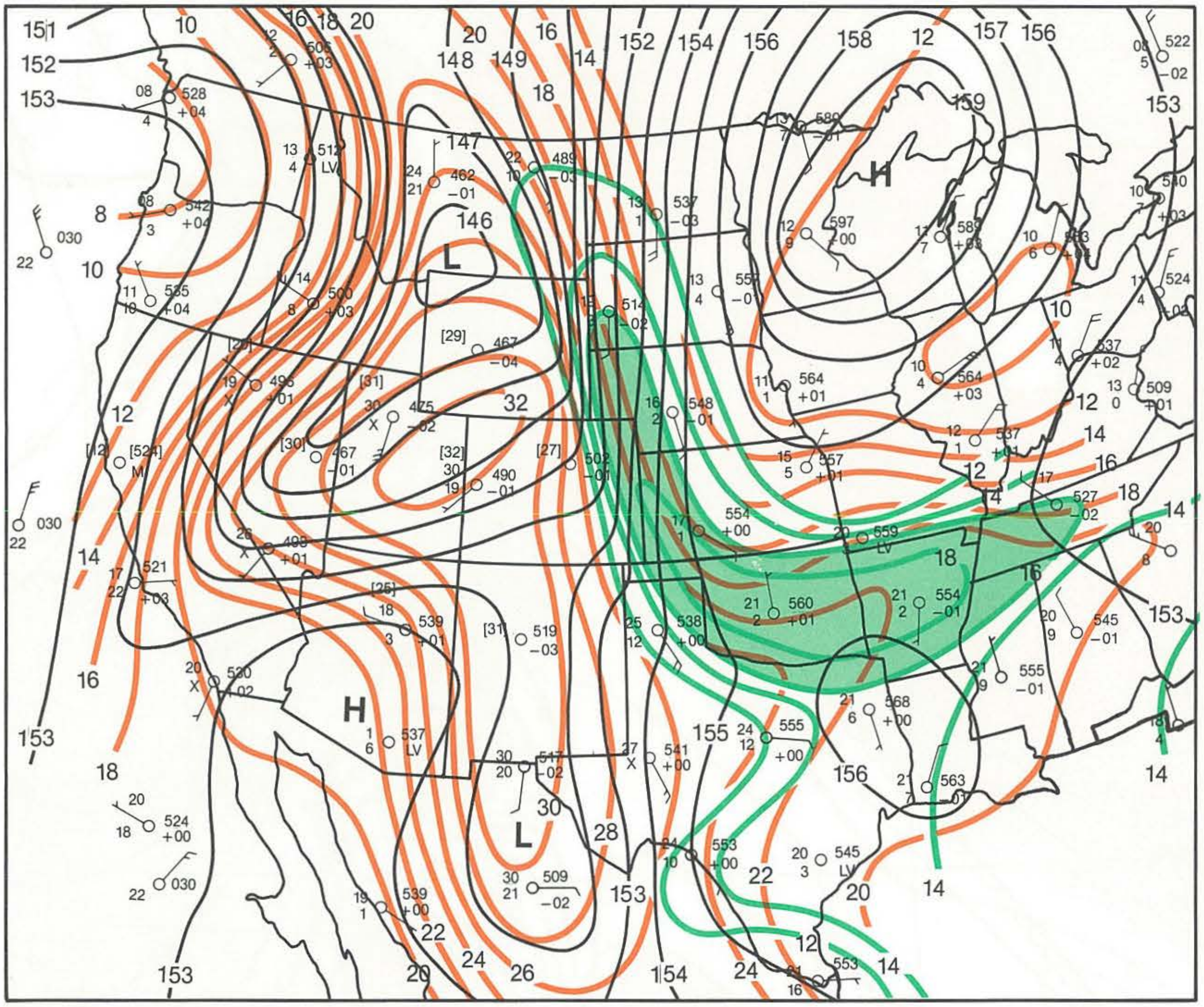


Figure 22. 850-mb analysis for 0000 GMT, 2 August 1985. Height contours (dam) and station plots are in black. Green-shaded area indicates dewpoint temperature ≥16°C. Orange lines represent isotherms (°C).

5. LARGER SCALE ENVIRONMENT AT 0000 GMT 2 AUGUST 1985

The Cheyenne storm was just getting under way at 0000 GMT. Low-level moisture had continued to increase in the southeasterly flow across northeastern and extreme eastern Colorado as shown on the surface chart for 2300 GMT, 1 August 1985 (Fig. 21) and the 850-mb chart for 0000 GMT, 2 August 1985 (Fig. 22). Note on the latter chart

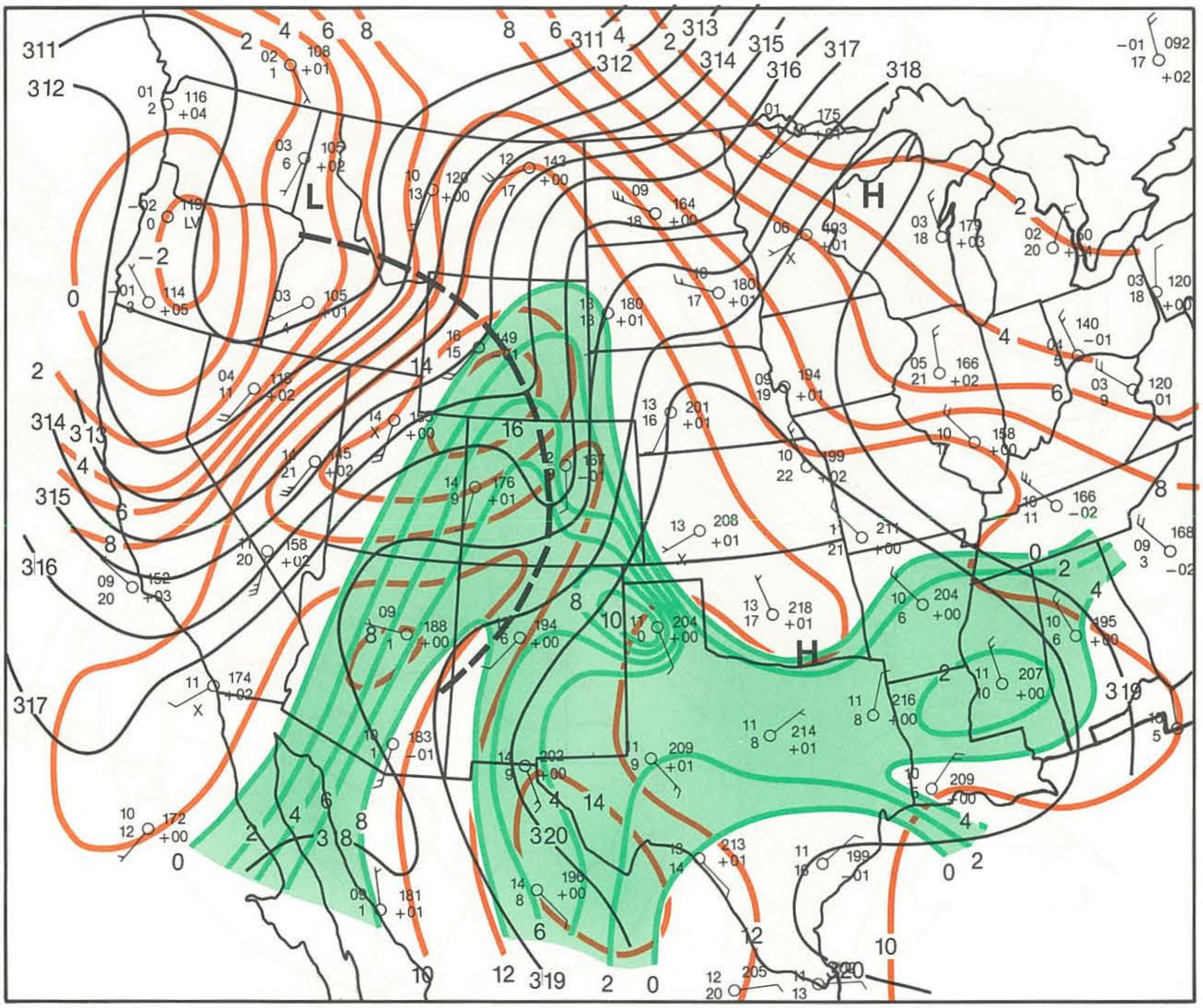


Figure 23. 700-mb analysis for 0000 GMT, 2 August 1985. Height contours (dam) and station plots are in black. Green-shaded area indicates dewpoint temperature ≥0°C. Orange lines represent isotherms (°C).

that the warmest temperatures are west of Cheyenne, and the low-level moist tongue extending into the southeast corner of Wyoming is quite narrow. This suggests that a narrow north-south zone of strong instability existed near Cheyenne where the best combination of steep lapse rates and low-level moisture was present. Low-level moisture diminished rapidly to the west of Cheyenne, while low-level temperatures decreased to the east. Air flowing into the Cheyenne area during the late afternoon had a trajectory for several hours in the sunshine.

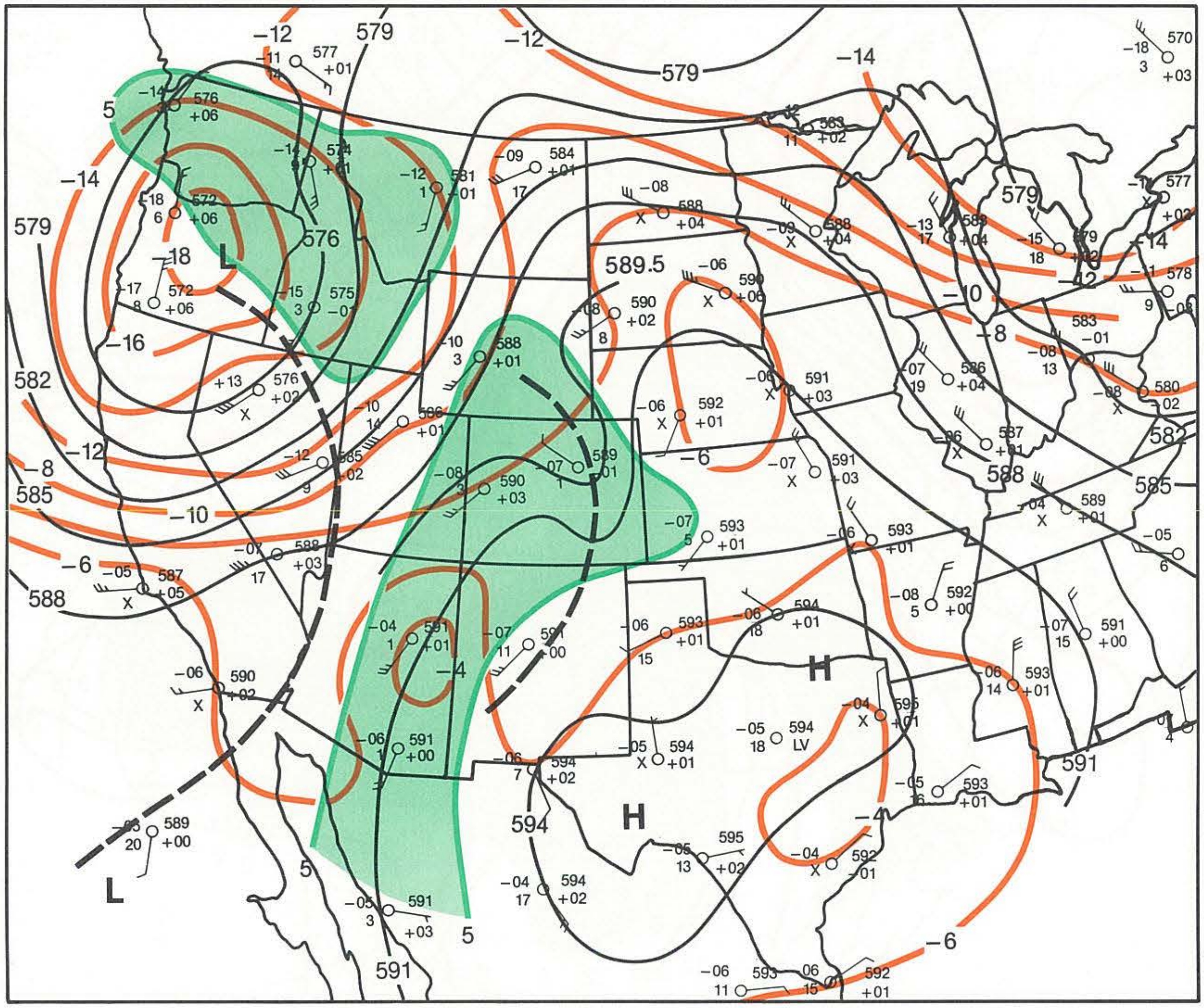


Figure 24. 500-mb analysis for 0000 GMT, 2 August 1985. Height contours (dam) and station plots are in black. Green-shaded area indicates dewpoint depression ≤5°C. Orange lines represent isotherms (°C).

The approaching short-wave trough is evident on the 0000 GMT 700-mb (Fig. 23) and 500-mb (Fig. 24) charts. It extended from near Yellowstone Park southeastward to west of Denver. Very warm air at 700 mb over south-central Wyoming and adjacent areas of Colorado and Utah, combined with cooling at 500 mb, had produced a deep mixed layer with nearly dry adiabatic lapse rates.

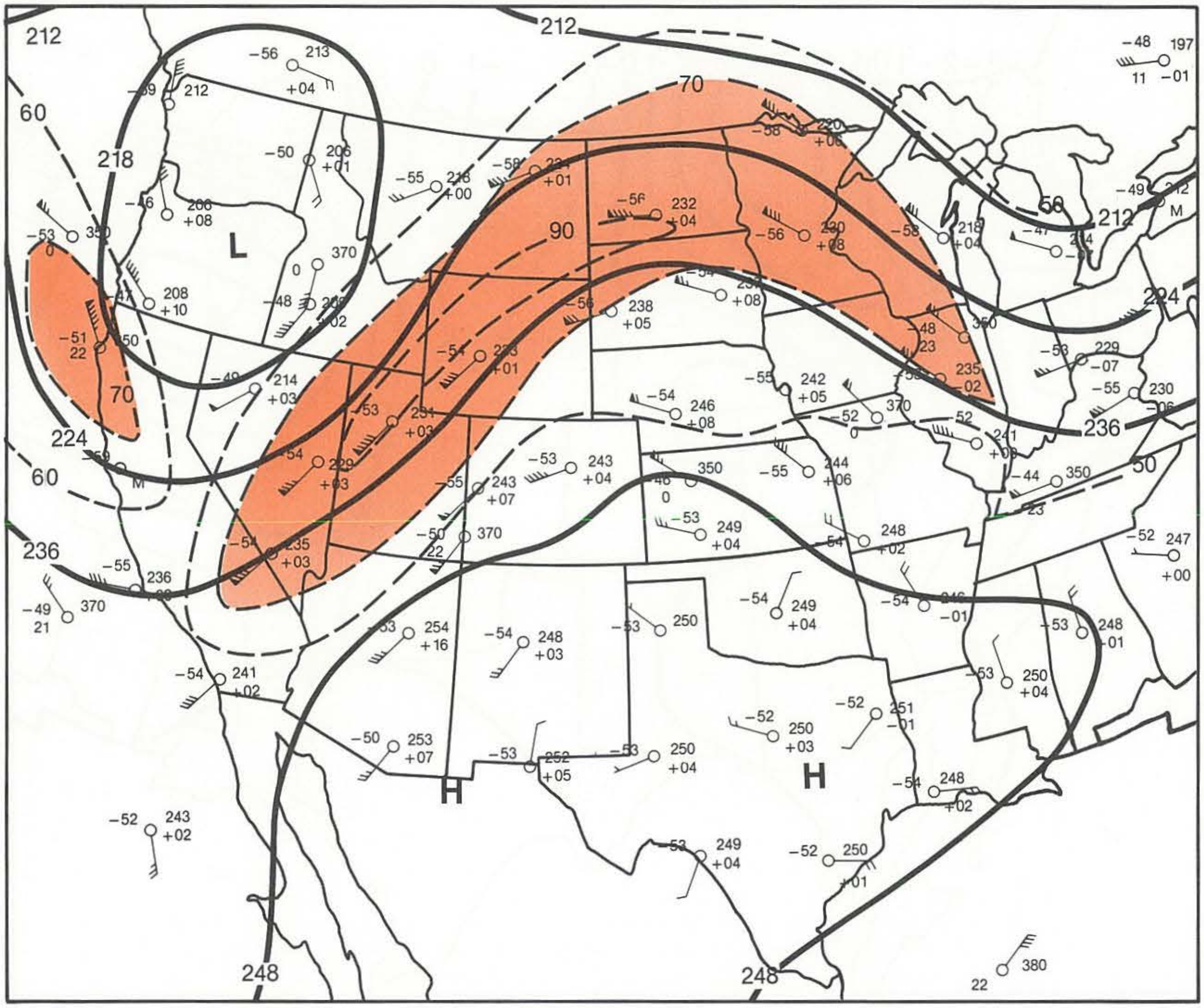


Figure 25. 200-mb analysis for 0000 GMT, 2 August 1985. Height contours (solid), isotachs (dashed) and station plots are in black. Heights are in dekameters (leading 1 is omitted; for example, 236 = 12360 m). Wind speeds are in knots; speeds ≥70 kt are shaded orange.

At 200 mb (Fig. 25) the axis of the jet stream had translated eastward to a line running from Las Vegas, NV, to Salt Lake City, UT, to near Bismarck, ND. A jet maximum of about 50 m s^{-1} was located over northwestern Wyoming, and Cheyenne lay in a region of relatively strong anticyclonic curvature and anticyclonic shear southeast of the jet axis.

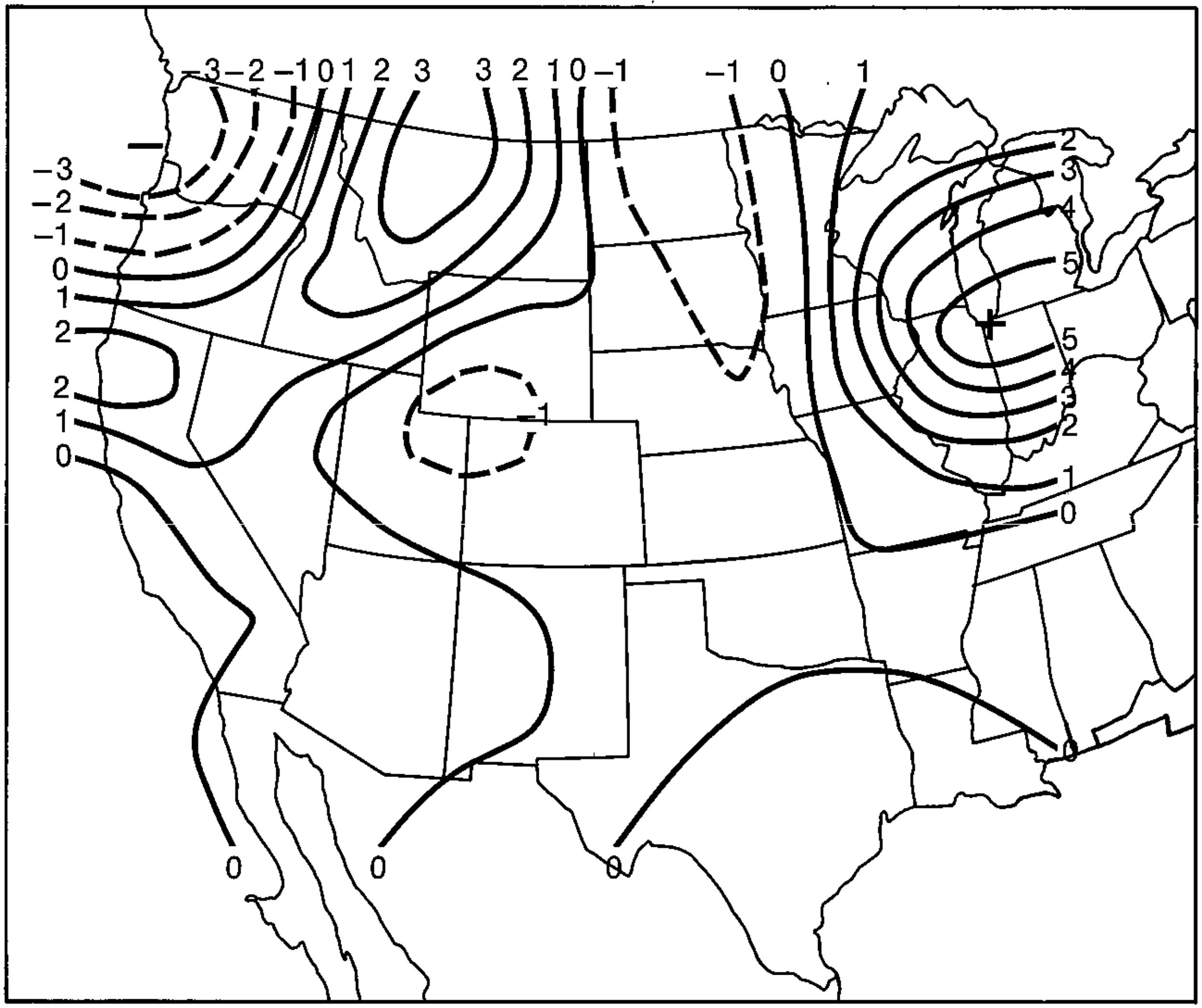


Figure 26. 600-mb divergence of Q vectors (10^{-17} s^{-3} mb^{-1}) for 0000 GMT, 2 August 1985.

The configuration of quasi-geostrophic forcing at 0000 GMT is shown in Figs. 26 and 27. The convergence of Q vectors indicates upward motion over the Cheyenne area, increasing with height, and stronger rising motion over southwestern Wyoming. The stronger upward motion in the upper troposphere, relative to the lower troposphere, suggests that vertical stretching also contributed to steepening lapse rates over southern Wyoming. The axis of strongest upward motion at 400 mb is situated very near Cheyenne, and extrapolation of this axis suggests that upward motion in the Cheyenne area would be peaking within a few hours.

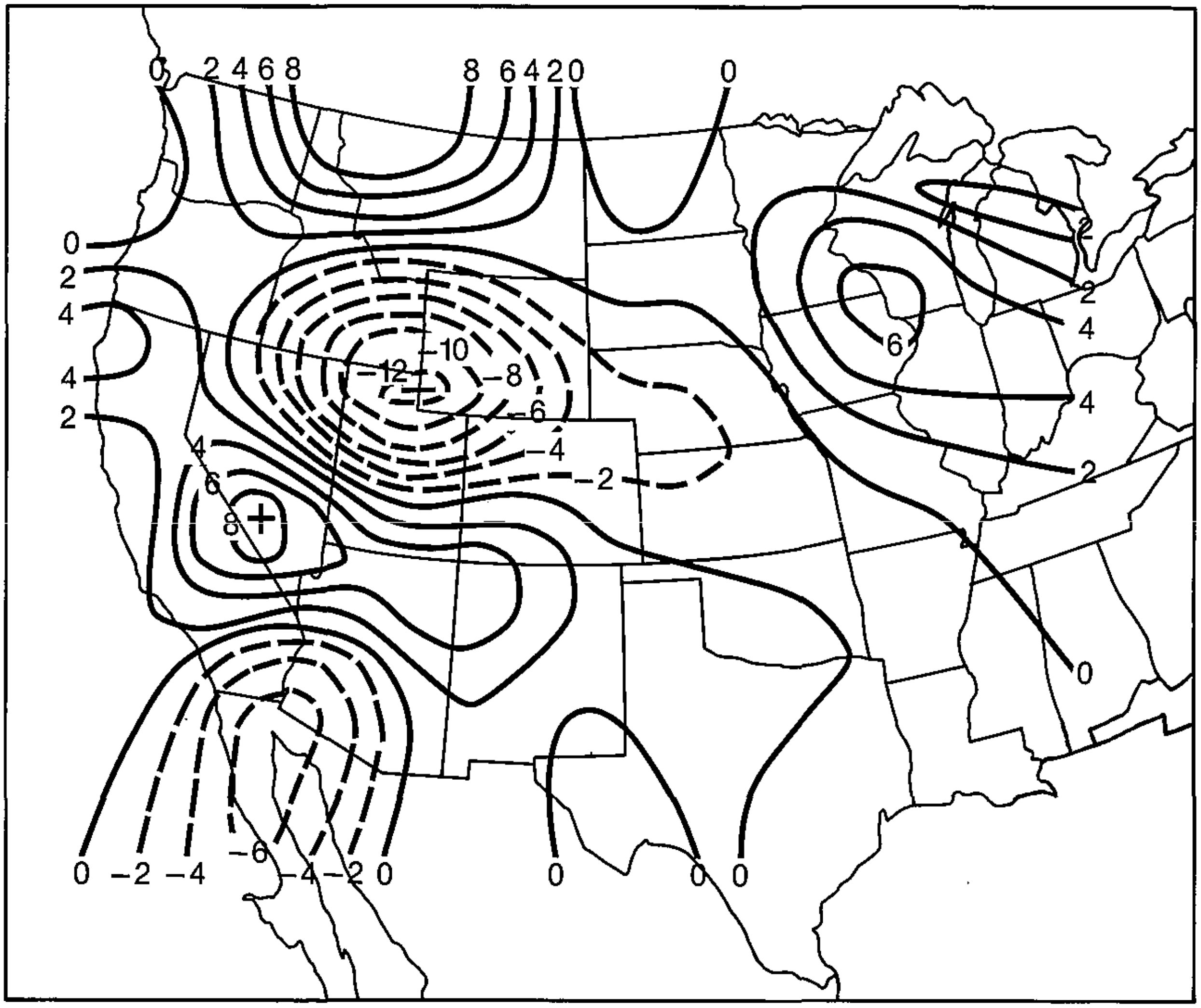


Figure 27. 400-mb divergence of Q vectors (10^{-17} s^{-3} mb^{-1}) for 0000 GMT, 2 August 1985.

A sounding was constructed for the Cheyenne area (Fig. 28), valid at the beginning of the storm (0000 GMT, 2 August 1985). The sounding shows a lifted index of -7 and 14.0 g kg^{-1} of water vapor present in the boundary layer. Strong veering of the wind is present in the boundary layer, and winds are light southerly from 700 mb to 500 mb. Above 500 mb, winds are west-southwesterly and increase in speed up to 28 m s^{-1} at 200 mb. A pressure-weighted vector mean wind was calculated for the layer from 800 mb to 200 mb above Cheyenne, valid at 0000 GMT. This calculation yielded a vector having a direction of 190° and a speed of 5.5 m s^{-1}. This vector mean wind is approximately equal

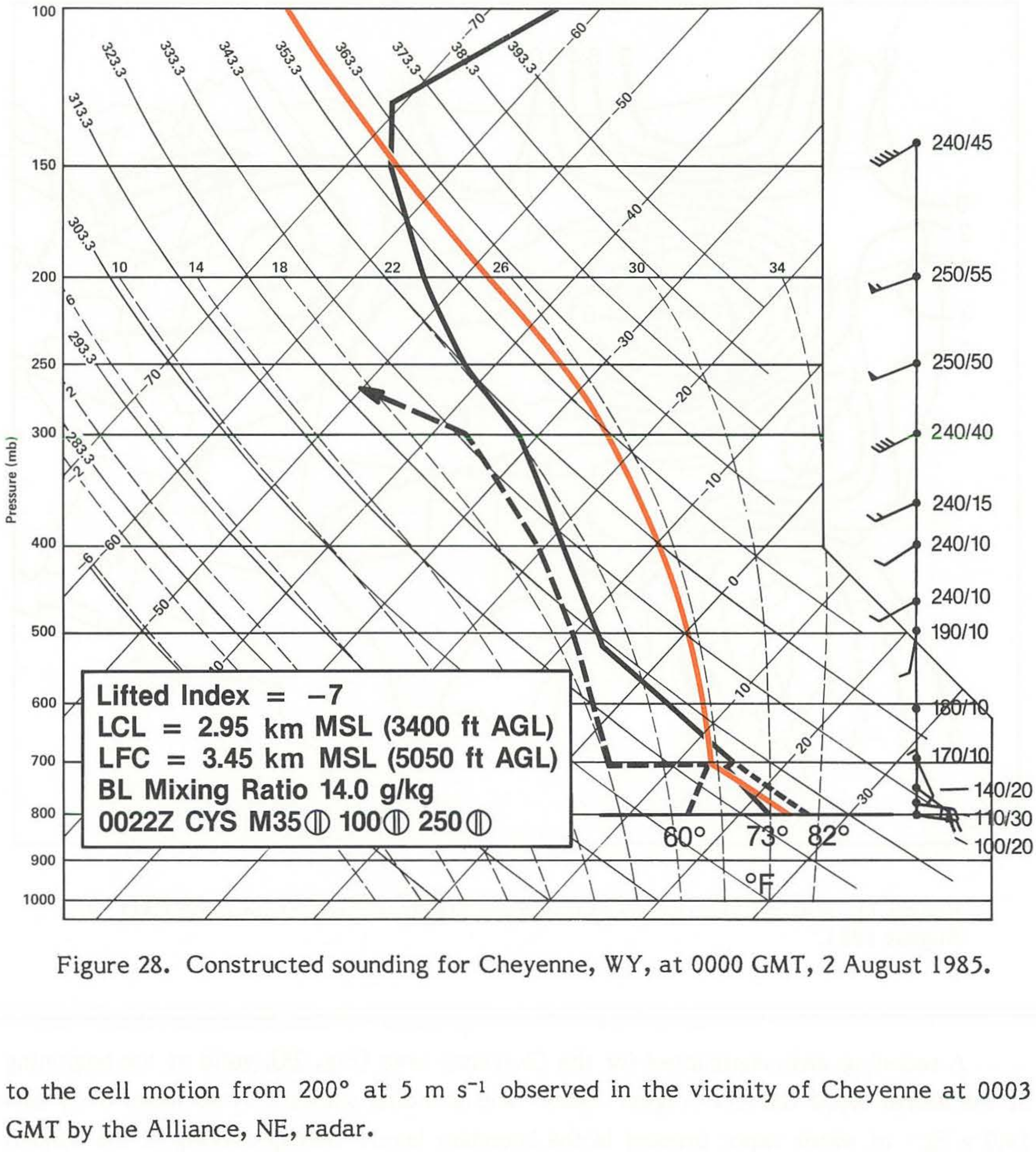


Figure 28. Constructed sounding for Cheyenne, WY, at 0000 GMT, 2 August 1985.

to the cell motion from 200° at 5 m s^{-1} observed in the vicinity of Cheyenne at 0003 GMT by the Alliance, NE, radar.

The computed vector mean wind is nearly normal to the Cheyenne Ridge and the cool air boundary created by downdrafts from earlier thunderstorm activity, both of which lie just south of Cheyenne. Thus, any new cells that develop on the cool air boundary or on the higher terrain south-southwest of Cheyenne would be expected to drift slowly north-northeast toward the city.

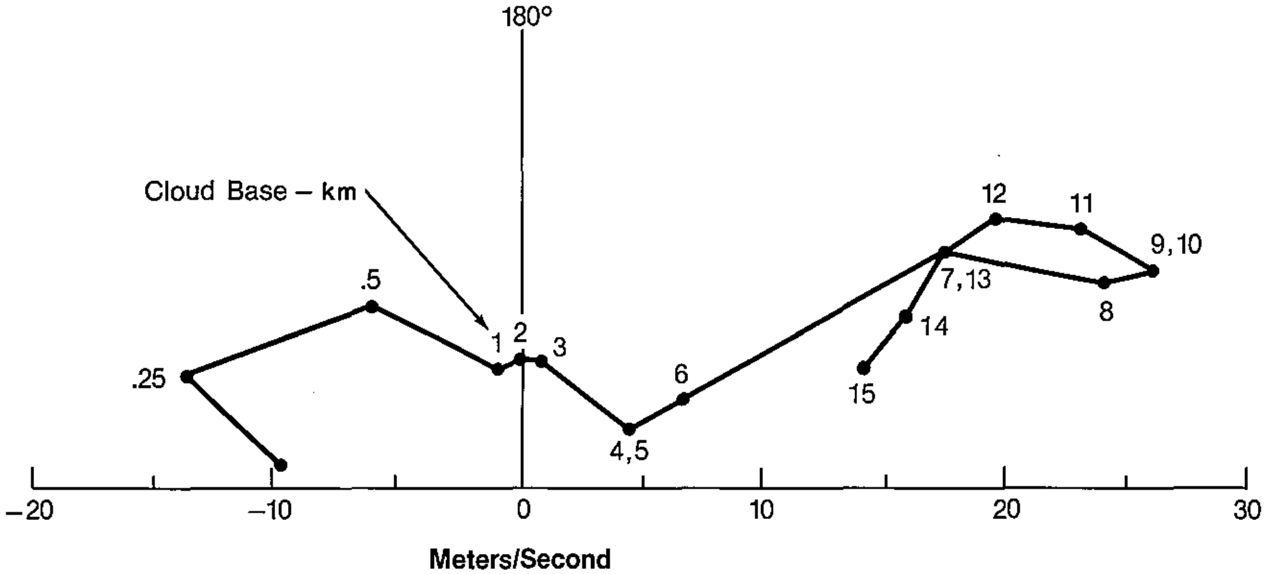


Figure 29. Vertical distribution of the horizontal winds at Cheyenne, WY, at 0000 GMT, 2 August 1985. Numbers along the trace are height (km) above Cheyenne.

The constructed sounding for the Cheyenne storm also indicates that a warm cloud (above freezing) depth of nearly 3 km would exist in an undiluted updraft. This depth is comparable with those in the Big Thompson and Rapid City flash flood cases. We believe that the unusual depth of warm cloud (for this region) promoted the formation of rain by coalescence processes, enhancing rainfall intensity and improving the precipitation efficiency of storm cells.

The hodograph for the area of the storm (Fig. 29) shows considerable veering of the wind below 1 km. Above cloud base, or at approximately 1 km, the shear vectors are generally west to east up to 10 km. The Bulk Richardson Number computed from the constructed Cheyenne sounding was 32. According to data and modeling results presented by Weisman and Klemp (1982), a value of 32 lies in the upper range of values associated with supercell storms (<50), and is also near the narrow range of values (35-50) where supercell and multicell storms are both possible.

6. CLOUD-SCALE STRUCTURE AND EVOLUTION OF THE CHEYENNE STORM

We identified important features of the Cheyenne storm structure and evolution by synthesizing data from several sources: (1) surface observations from the Cheyenne WSFO; (2) a series of photographs taken from Cheyenne and Laramie, and Fort Collins, CO; (3) reflectivities from two conventional radars; and (4) Doppler reflectivity and velocity data from a single radar. Unfortunately, the storm was overhead and within ground clutter of the Cheyenne WSFO radar, rendering the data unsatisfactory for analysis.

Radar data were obtained from National Weather Service WSR-57 radars at Alliance, NE, and Limon, CO. In addition, a research Doppler radar (the National Center for Atmospheric Research CP-2), situated 8 km southeast of Boulder, CO, was operating during the afternoon and early evening of 1 August 1985. It collected valuable data during the formative stages of the evolving storm. At a range of 135 km and an elevation angle of 0.7°, the radar beamwidth is about 2.3 km and centered about 2.6 km above ground level over Cheyenne.

6.1 The Multicellular Formation Stage

As seen in Fig. 19, an arc-shaped line of thunderstorms was situated just northeast through southeast of Cheyenne at 2229 GMT 1 August 1985. The thunderstorm southeast of the Cheyenne WSFO had developed on the gust front generated by earlier thunderstorm activity, after the front had moved through the city. The southern end of this line of thunderstorms and cumulus congestus is clearly visible in the 2255 GMT satellite picture (Fig. 30). An interesting event occurred near the southwestern end of this line as seen on the 2301 GMT satellite picture (Fig. 31). Note the hole in the convective cloud in that location. It appears to be the result of a downdraft, which was reaching the ground as the convective cloud began to dissipate. The satellite picture at 2320 GMT (Fig. 32) shows a growing circular ring of clouds, which suggests that the downdraft was spreading out in all directions. The cloud ring apparently reflects new cloud growth along an arc where the downdraft air was converging with environmental air. The northern part of the arc was propagating north toward the Cheyenne Ridge, embedded in the low-level southeasterly flow. New growth appears to be occurring just south of the Colorado/Wyoming border where the cloud ring was interacting with the earlier northeast-southwest cloud line.

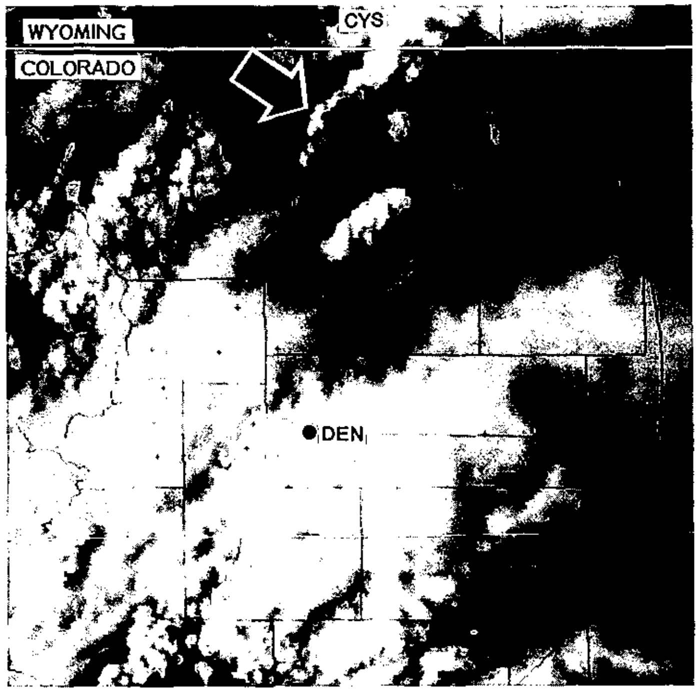


Figure 30. GOES-West visible (1-km-resolution) image for 2255 GMT, 1 August 1985. Arrow indicates location of dissipating cloud and resulting propagating arc cloud. Locations of Denver (DEN) and Cheyenne (CYS) NWS Forecast Offices are indicated.

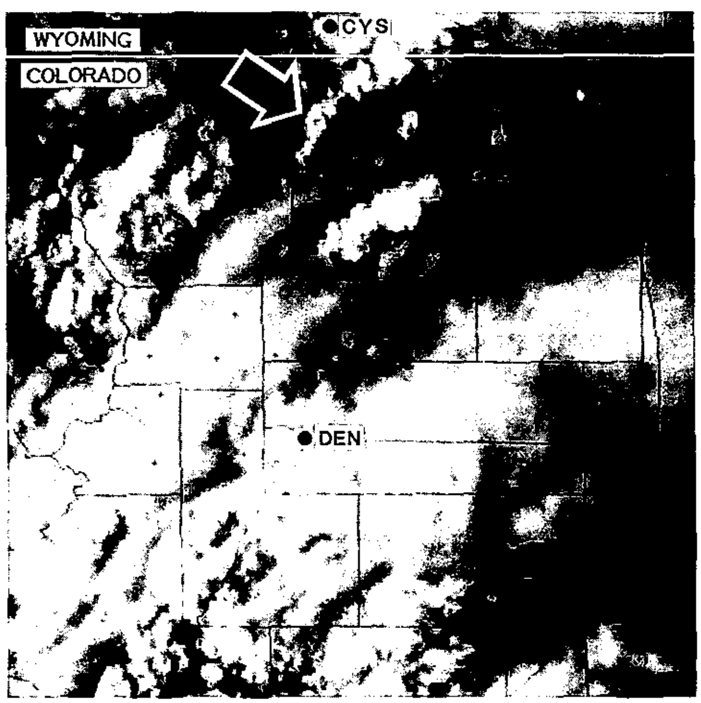


Figure 31. As in Fig. 30, but for 2301 GMT, 1 August 1985.

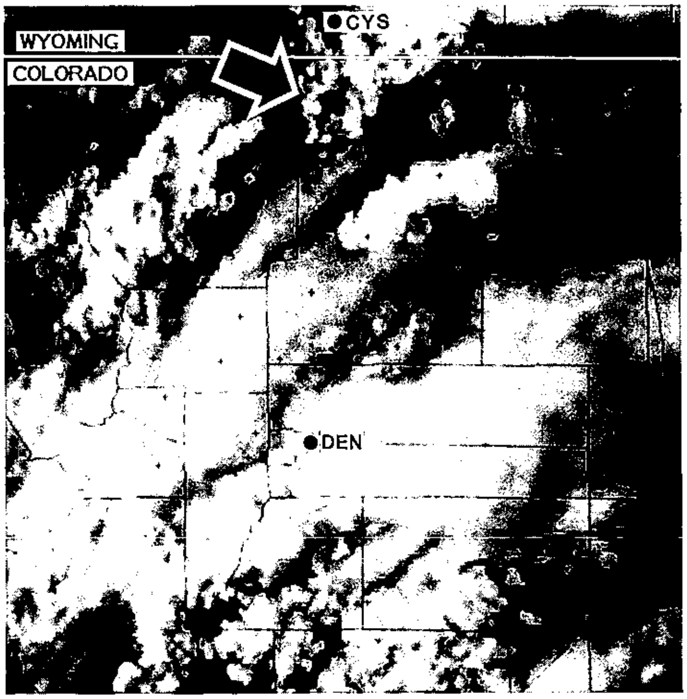


Figure 32. As in Fig. 30, but for 2320 GMT, 1 August 1985.

As the northward-moving arc line reached the vicinity of the Cheyenne Ridge summit, thunderstorms rapidly developed westward. This development is evident just north of the Colorado-Wyoming border in the 2335 GMT radar reflectivity (Fig. 33). The new thunderstorm development was apparently a response to the increase in the low-level convergence and lifting along an east-west zone where the two gust fronts interacted with one another and with the Cheyenne Ridge. The new convective cells provided the initial building blocks for the Cheyenne storm.

These new cells drifted northward while intensifying westward to form an east-west multicellular thunderstorm system as depicted by the 0020 GMT radar reflectivities (Fig. 34). Hail first began to fall at the Cheyenne WSFO around this time, while the Alliance radar detected a 13.4-km echo top on the easternmost cell. The initial hailfall ended 15 min later at 0035 GMT; 1-cm to 2.5-cm hailstones were reported in various sections of the metropolitan area. CP-2 radar depiction at 0030 GMT (Fig. 35) showed that the westernmost echoes were merging, intensifying reflectivities in that portion of the line. By 0045 GMT, two new vigorous cells developed south-southwest of the preceding east-west storm zone. These new cells intensified rapidly and moved north-northeast, accreting to the original multicellular thunderstorm system and creating a pronounced wave-shape configuration in the radar reflectivities.

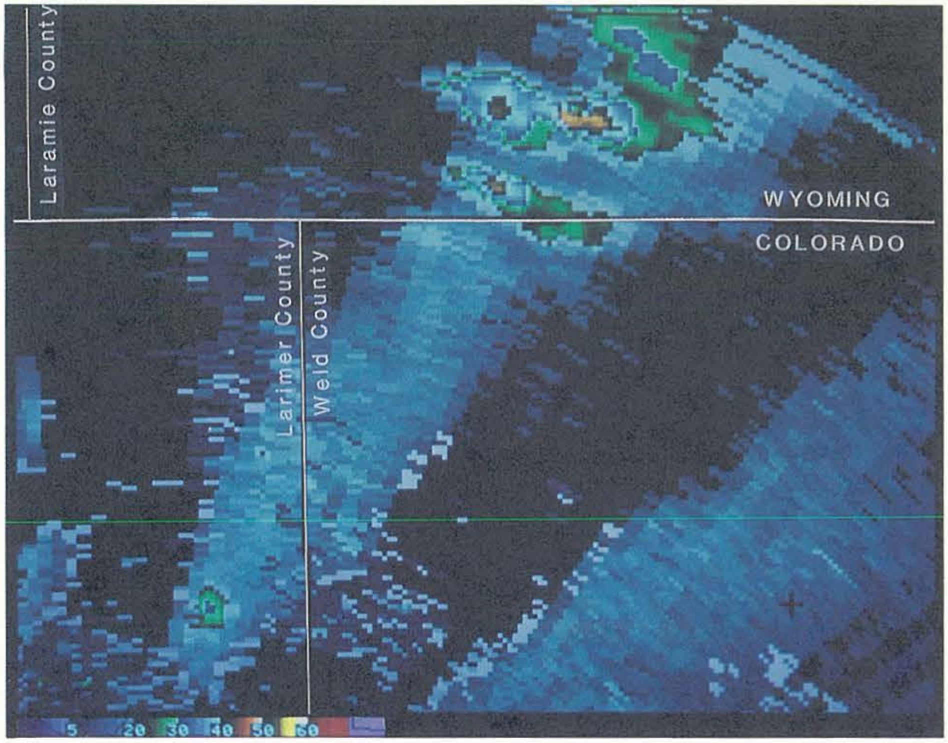


Figure 33. NCAR CP-2 radar reflectivity at 2335 GMT, 1 August 1985.

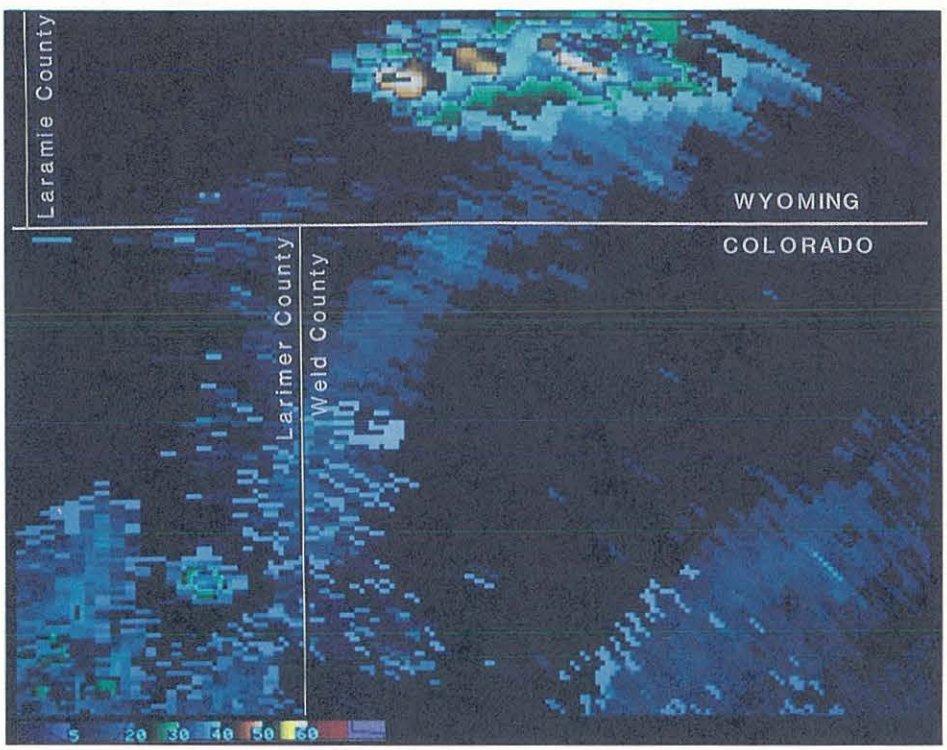


Figure 34. NCAR CP-2 radar reflectivity at 0020 GMT, 2 August 1985.

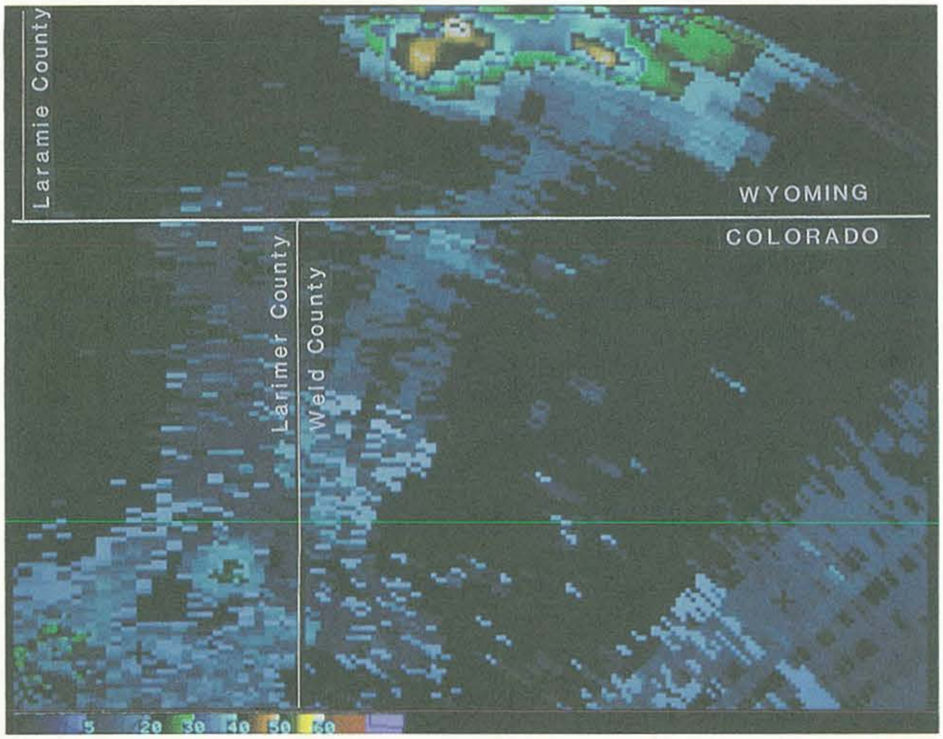


Figure 35. NCAR CP-2 radar reflectivity at 0030 GMT, 2 August 1985.

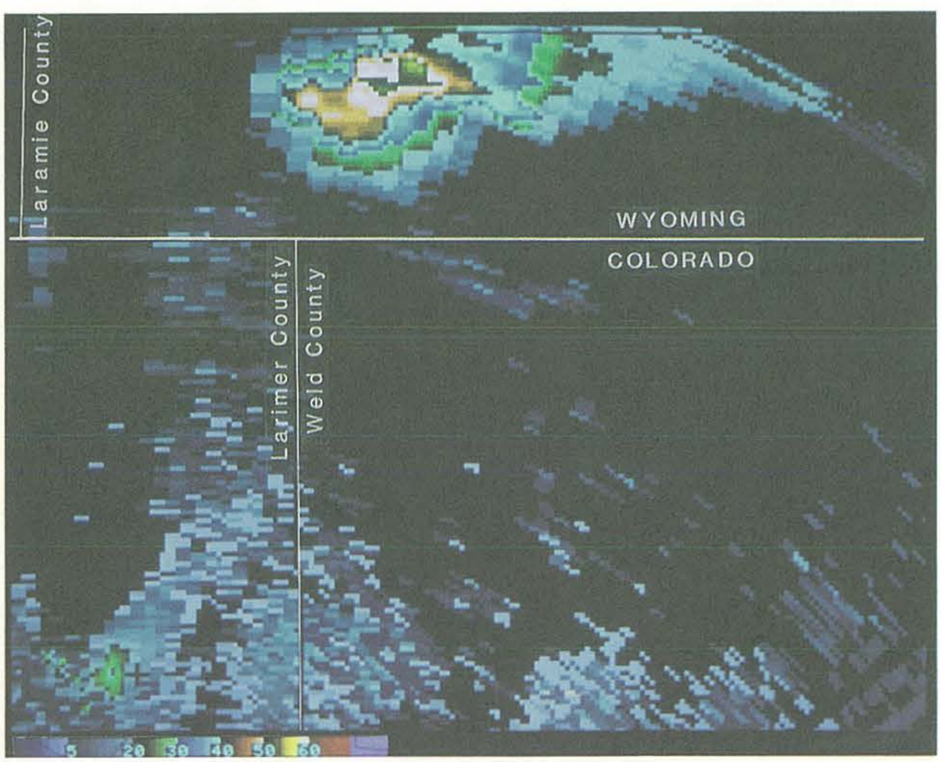


Figure 36. NCAR CP-2 radar reflectivity at 0105 GMT, 2 August 1985.

6.2 The Supercell Stage

At 0050 GMT, CP-2 Doppler radial velocity data first indicated the formation of a mesocyclone circulation in the strong echo over Cheyenne, and hail up to 1.6 cm began at the WSFO 3 min later. The CP-2 radar reflectivity pattern at 0105 GMT (Fig. 36) also suggests that the storm had evolved from a multicellular thunderstorm system to take on certain supercell characteristics (Browning, 1964; Lemon, 1980). The pattern indicates one huge, wave-shaped cell with a bounded weak-echo region on the southeast flank of the storm and reflectivities in excess of 55 dBZ. Cheyenne WSFO reported thunder overhead and stationary, with heavy rainfall and hailfall. Storm tops had reached 16.46 km as measured by the Alliance WSR-57 radar.

A small tornado picked up dust and debris between 0105 GMT and 0110 GMT near Interstate 80 a few miles west of the city, then lifted back into a rotating wall cloud. The lowered and ragged cloud base associated with the large rotating updraft of the supercell is seen in Fig. 37. Another tornado touchdown was observed for 2 min (0125-0127 GMT) by a PROFS (Program for Regional Observing and Forecasting Services) storm intercept team. A funnel cloud was observed from the WSFO near the site of the first tornado touchdown at 0124 GMT and was estimated to be 5 miles southwest of the station. The time and location of this funnel cloud indicate that it was probably associated with the large rotating updraft that produced the two small tornadoes, and was probably the same vortex as the second tornado reported.

Radar observation from Alliance at 0129 GMT indicated that the echo top was >18.3 km. The next report at 0137 GMT stated that the storm echo had achieved its greatest height (19.5 km), and contained an extremely intense echo core (>56 dBZ); the strongest low-level reflectivity gradient was positioned 5 miles southwest of the city. The 0137 GMT radar report out of Alliance also noted an apparent rotation to the storm echo. Corroborative reports from Alliance WSR-57 and CP-2 radars, and from trained meteorological observers in the area confirmed the supercell structure of the storm at this stage, although the radars were too distant for details of the internal characteristics of the echo to be resolved satisfactorily. On the basis of accepted models of supercell structure, and the observed position of the main rotating updraft, it appears that the storm was positioned to place downtown Cheyenne in the region of continuous heavy rain and hailfall.

Figure 37. The lowered and ragged cloud base associated with the updraft region of the storm between 0105 and 0110 GMT. Photograph was taken by NOAA storm intercept team from a location on Interstate 25 about 8 km south of Cheyenne, looking northwest.

The supercell structure was maintained for nearly 2 hours as the storm remained quasi-stationary over the city of Cheyenne. Photographs taken between 0155 GMT and 0204 GMT from Laramie, WY (about 65 km west-northwest of Cheyenne) show the large stationary supercell being invigorated as smaller buoyant elements (feeder clouds) developed several kilometers south-southwest of Cheyenne and moved north-northeastward to be absorbed into the large, rotating storm (Fig. 38).

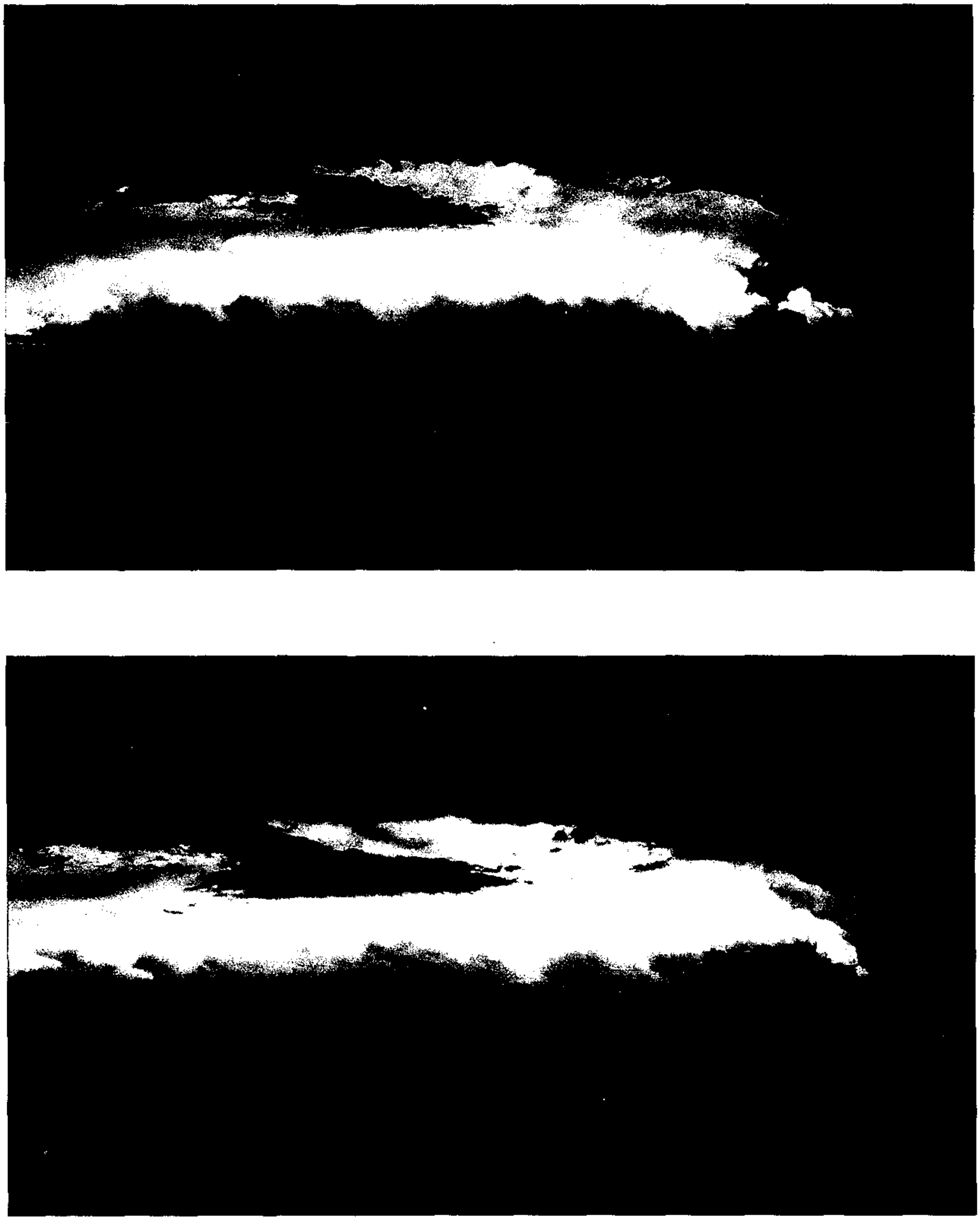


Figure 38. The Cheyenne storm seen from Laramie, WY, looking east-southeast. Note the small convective clouds merging with the storm from the right (south) side. (Top) 0155 GMT; (bottom) 0158 GMT. (Photos by John D. Marwitz.)

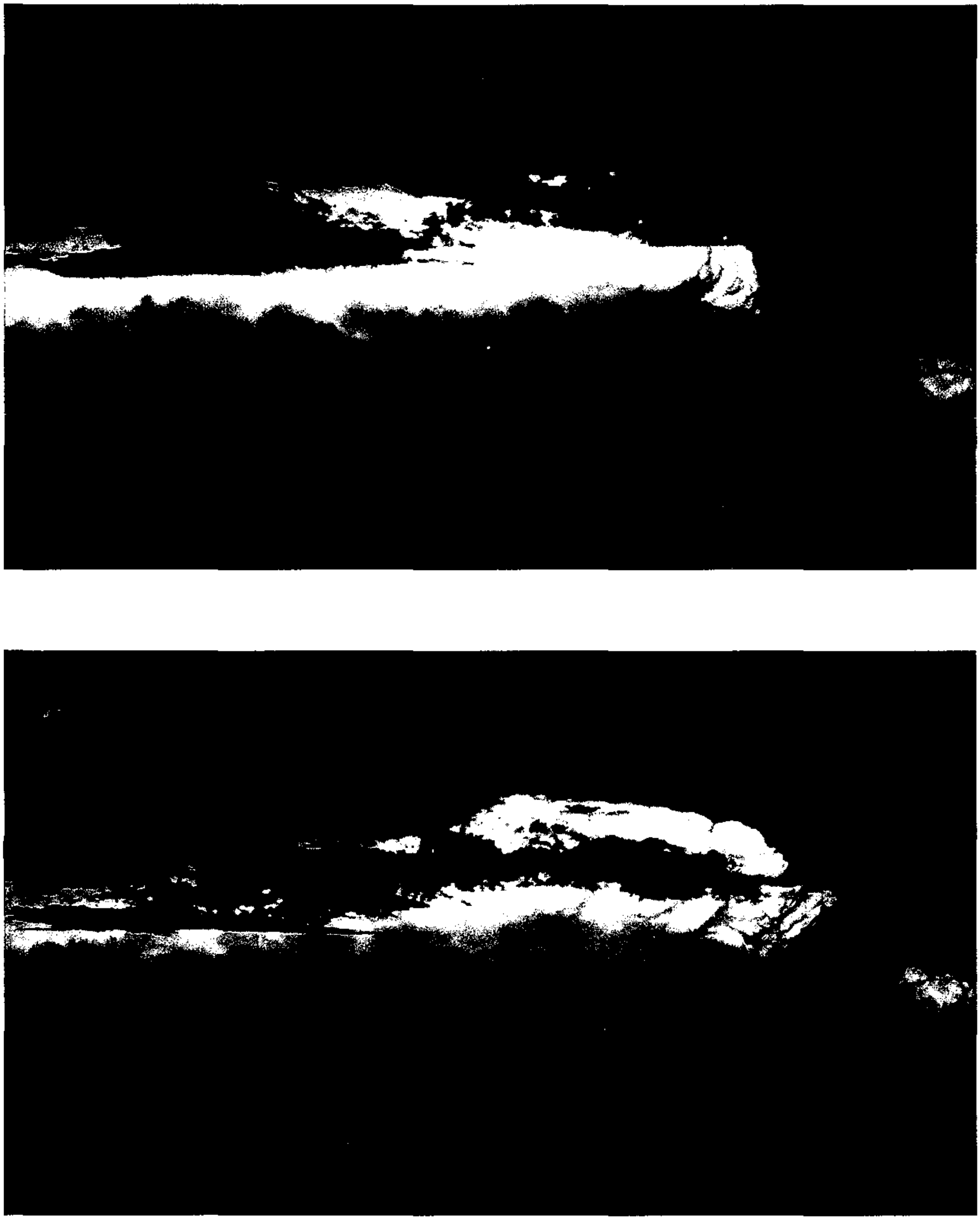


Figure 38 (continued). (Top) 0201 GMT; (bottom) 0204 GMT.

6.3 Storm Motion

Observations strongly suggest that storm motion changed as the storm transformed from a multicellular thunderstorm system to a rotating supercell. This transformation apparently occurred between 0030 GMT and 0100 GMT. Prior to the transformation, thunderstorm cells embedded in an east-west zone were drifting slowly northward, consistent with the pressure-weighted vector mean wind from 190° at 5.5 m s^{-1}. After the transformation to a rotating supercell, the storm became nearly stationary for a 2-h period. We offer a hypothesis for this observed storm behavior.

Rotunno and Klemp (1985) proposed from the results of numerical experiments that storm propagation transverse to the environmental wind shear is dynamically induced by the strong rotation at middle levels that may develop along the flanks of supercell storms. This rotation lowers the pressure locally, which leads to the development of an upward nonhydrostatic pressure gradient force, new updraft growth, and lateral displacement of the main updraft. Rotunno and Klemp found that a dynamically induced vertical pressure gradient is alone capable of generating new growth on the updraft flank that is transverse to the wind shear. Furthermore, these forces promoting transverse propagation continue to operate even in the absence of precipitation-driven downdrafts. The modeling results suggest that dynamically induced vertical pressure gradients largely drive a supercell's updraft circulation, as well as laterally displacing it.

Lilly (1986a, 1986b) proposed that helicity (helical circulations) promotes the longevity and transverse propagation of supercell storms. Helicity is defined as the dot product of the velocity and vorticity vectors, or $\vec{H} = \vec{V} \cdot \vec{W}$. It is seen from this definition that helical flow is favored when the vertical components of velocity and vorticity at various levels of the storm are closely correlated. Under optimum conditions for helical flow, velocity and vorticity vectors are parallel (the dot product of velocity and vorticity becomes the product of their magnitudes), and Beltrami flow exists. Under the assumption of Beltrami flow, and the further assumption that the storm adjusts its propagation rate so as to equalize the Beltrami flow parameter between the storm disturbance and the mean flow, the propagation rate of the storm transverse to the mean wind shear can be computed.

The transverse propagation speed for a storm embedded in a mean flow is given, following Lilly (1986b), by

$$c_t = (1+2h^2/w^2)^{-1/2}\, \pi^{-1} h\, du/dz, \tag{1}$$

where h and w correspond to the height and width of the storm updraft, and du/dz is the mean wind shear of the environment. If we assume that the mature Cheyenne storm occurred under conditions approximating Beltrami flow, we can estimate the propagation rate of the storm transverse to the mean wind shear, using equation (1). In the case of the Cheyenne storm, h is estimated from radar observations to be 15 km, and w is estimated to be 7.5 km from visual observations taken by a storm intercept team. The correct wind shear value to insert in (1) is debatable, since the storm extended beyond the tropopause into a layer where wind decreased with height. Therefore, two values of wind shear were used to compute c_t. In the first case, the shear between 0.25 km and 15 km was used. The shear vector of 270° at 28 m s^{-1} yielded a value of 0.0019 s^{-1} for the layer. Using this value in (1) to solve for c_t yields a propagation rate of 3.0 m s^{-1} transverse to the wind shear, or directed from the north. The addition of this vector to the pressure-weighted mean vector wind of the environment gives a small storm motion vector of 202° at 2.6 m s^{-1} (Fig. 39a).

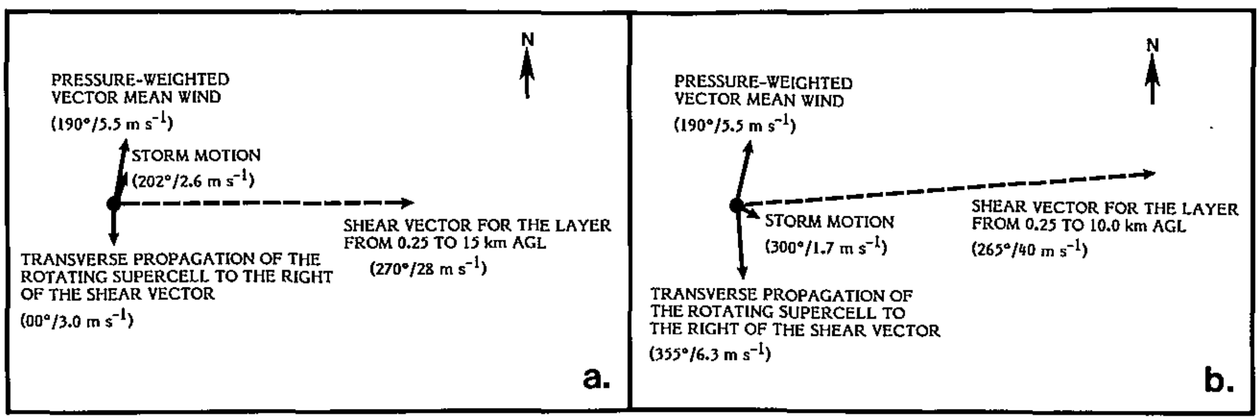


Figure 39. The vector mean wind of the storm environment, mean wind shear, transverse propagation rate, and computed storm motion for (a) a layer between 0.25 and 15 km AGL, and (b) a layer between 0.25 and 10 km AGL, constructed for 0000 GMT, 2 August 1985.

The calculation for c_t was repeated using the mean wind shear below 10 km. In this case, the transverse propagation rate was found to be a vector directed from 355° at 6.3 m s^{-1} (Fig. 39b). The addition of this vector to the pressure-weighted mean vector wind of the environment gives a small motion vector from 300° at 1.7 m s^{-1} for this set of conditions. The effect of the transverse propagation in both cases is to counteract substantially the forcing of the pressure-weighted mean vector wind of the storm environment and to slow the storm markedly.

It is interesting to note the temporal variations of wind and pressure during the storm as observed at the Cheyenne WSFO (Fig. 40). Wind and pressure were relatively steady during the first hour of the supercell's existence (0050-0150 GMT). This suggests a nearly stationary storm. However, the shifting winds and changing pressure during the second hour (0150-0250 GMT) were consistent with a thunderstorm microscale high-pressure system, moving slowly southeastward just south of the Cheyenne WSFO. This latter storm movement is quite consistent with the storm motion computed using the maximum tropospheric wind shear in (1).

Photographs of the storm (Fig. 38) also depict this transverse propagation. Small buoyant elements (their updrafts are small compared with the size of the supercell updraft) moved into the southern flank of the supercell and were absorbed. There is visual evidence that these buoyant elements, upon entering the storm from the south, rapidly intensified the supercell updraft on its south flank, essentially producing a transverse displacement of the storm updraft.

A very important factor in producing this quasi-stationary storm was the combination of the relatively strong easterly winds at lower levels and the light southerly winds at middle levels. The hodograph based on this particular configuration of winds indicates an atmosphere capable of supporting supercell structure, and simultaneously yielding a pressure-weighted vector mean wind for the environment small enough, relative to the ground, that transverse propagation could bring the storm to a standstill.

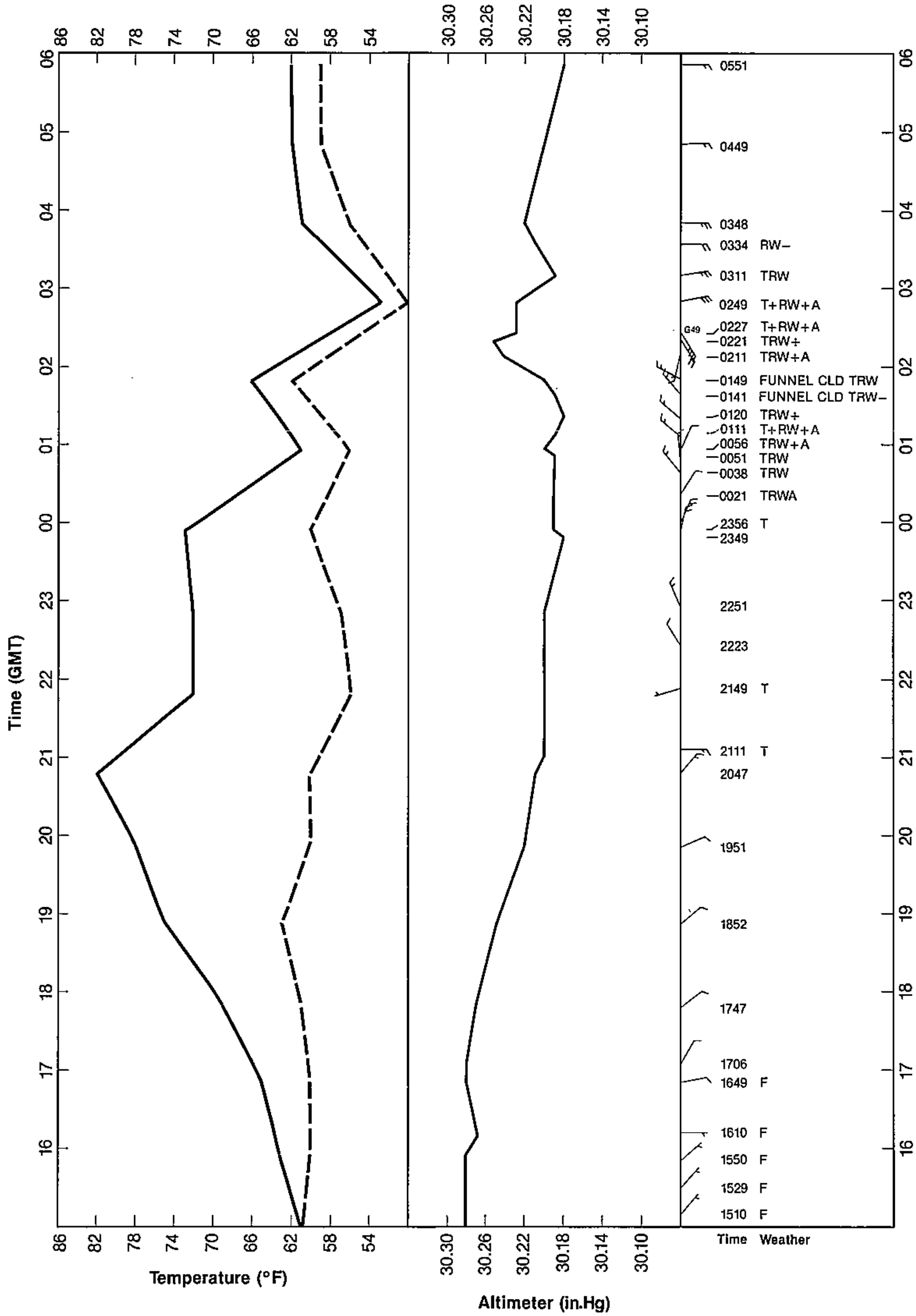


Figure 40. Temporal variations of temperature, pressure, surface wind, and current weather during the storm as measured at the Cheyenne WSFO.

6.4 Storm Dissipation

As seen in the 0000 GMT 2 August 1985 upper-air data, a short-wave trough in the middle troposphere (Figs. 23 and 24) was approaching Cheyenne from the southwest, and quasi-geostrophic forcing (Fig. 27) was about to peak in the Cheyenne area. The approaching trough in the middle troposphere is revealed by the vertical wind profile for Platteville, CO (Fig. 41). Note the trough passage shortly before 0000 GMT, 2 August 1985 at levels between 5 and 8 km. Since Platteville lies approximately 100 km south of Cheyenne and the trough is oriented northwest to southeast (Fig. 42), one would expect the trough to reach Cheyenne at about 0200-0300 GMT. This is approximately when the Cheyenne storm began to dissipate and accelerate southeastward. Also note in Fig. 41 the slight low-level wind shift (from south to southwest) at Platteville about 2300 GMT, 1 August. Analysis of the PROFS mesoscale surface network shows this wind shift to be part of a low-level trough moving northeast through the network (Fig. 43). Although this low-level wind shift occurred at approximately the same time the middle-level trough passed, the two do not seem to have been directly connected. The low-level wind shift is believed to have been caused by weak outflow from widespread afternoon thunderstorms

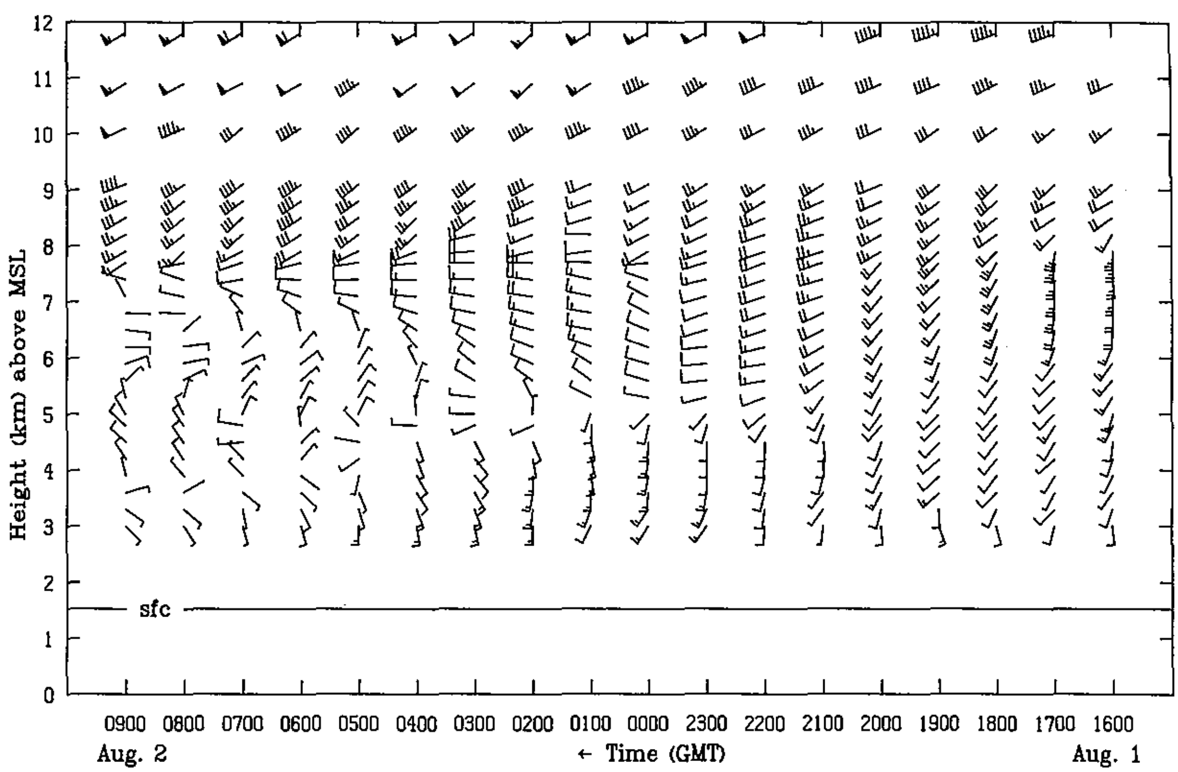


Figure 41. Vertical wind profiles observed at Platteville, CO, during the storm period.

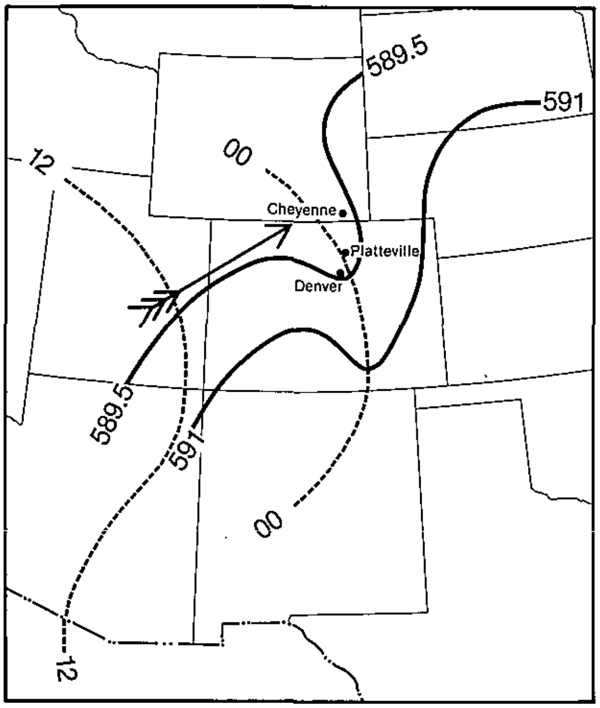
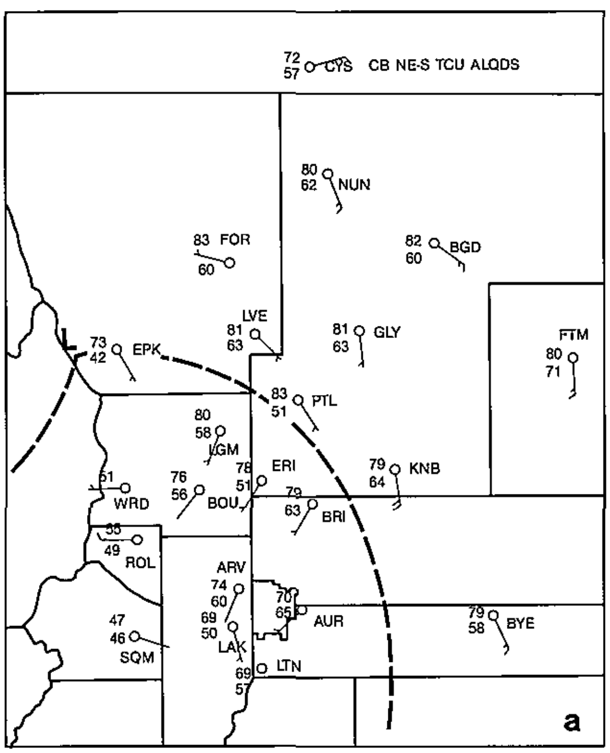


Figure 42. Analysis of 500-mb trough positions at 1200 GMT, 1 August and 0000 GMT, 2 August (dashed lines) and 500-mb heights (dam; solid lines) at 0000 GMT, 2 August. Arrow indicates 12-h trajectory of short-wave trough.



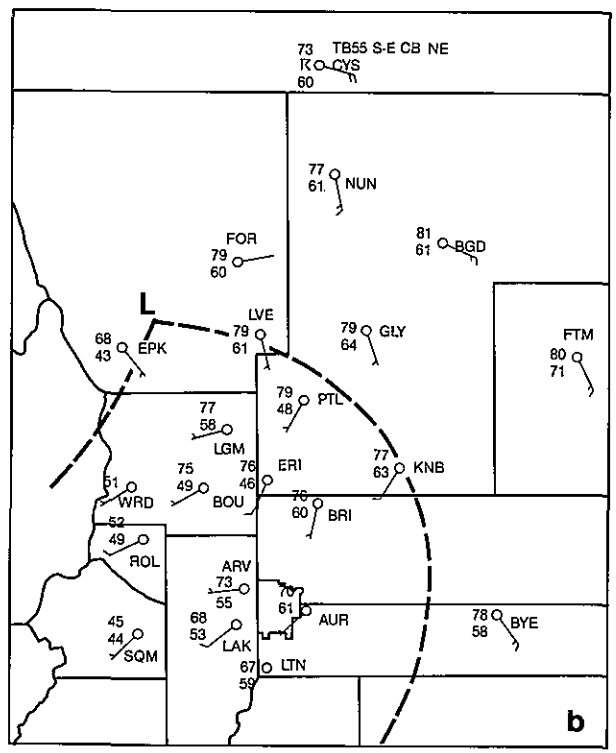


Figure 43. PROFS mesoscale network data. Dashed lines represent the wind shift line. (a) 2255 GMT; (b) 0000 GMT.

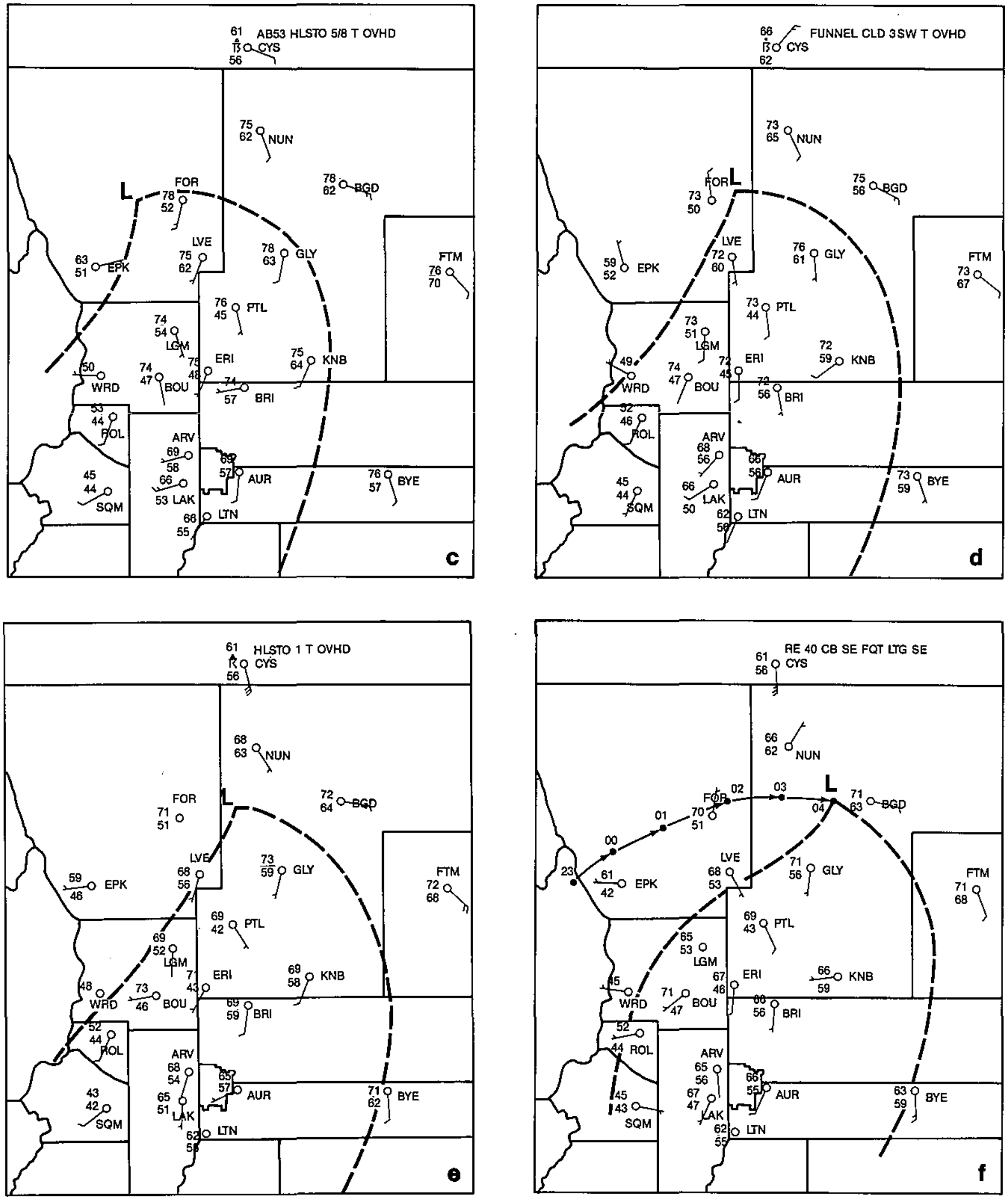


Figure 43 (continued). (c) 0100 GMT; (d) 0200 GMT; (e) 0300 GMT; (f) 0400 GMT. Arrow-dot line in (f) marks the progression of the low center.

in the mountains and foothills northwest through southwest of the Denver metropolitan area. Nevertheless, there appears to have been a weak wave on the western end of this wind-shift line, just west of Estes Park (EPK) at 2255 GMT (Fig. 43a). During the next 4 h the low-level wave approached Cheyenne from the southwest, eventually turning more eastward and passing about 50 km south of the city between 0200 GMT and 0300 GMT (Fig. 43d,e). It is likely that this wave increased the low-level convergence in the general storm area as it approached.

It is interesting that the top of the Cheyenne supercell collapsed between 0200 GMT and 0300 GMT. This apparently occurred with the arrival of the middle-level trough and as the surface wave passed eastward, south of the city. The collapse of the storm top was accompanied by 8.92 cm of rain at the Cheyenne WSFO. The storm then accelerated toward the southeast and rapidly dissipated.

7. SUMMARY AND CONCLUDING REMARKS

Synoptic-scale conditions were ripe for severe thunderstorms in a narrow zone of southeastern Wyoming where steep lapse rates and low-level moisture combined to generate a conditionally unstable airmass. West of this zone the low-level moisture diminished, while east of this zone the boundary layer remained too cool to support deep convection. Unfortunately this narrow strip of atmospheric instability covered the Cheyenne area. Quasi-geostrophic processes were operating to produce large-scale lifting over southeastern Wyoming and to steepen lapse rates through vertical stretching. Additionally, indications at 0000 GMT, 2 August 1985, were that large-scale upward motion would be peaking in the Cheyenne area within the next few hours.

It is difficult to assess the relative importance of the Cheyenne ridge and the downdraft front generated by early thunderstorms in providing a mechanism for new cloud growth just south and southwest of Cheyenne. The two features were nearly colocated and therefore their separate roles could not be distinguished with the data available.

A northward-propagating arc line of clouds, which formed from a dissipating cell south-southwest of Cheyenne during the late afternoon, apparently provided enhanced lifting for new cloud growth. This was evident in the sudden growth of the east-west line of cells as it reached the general location of the initial downdraft boundary and the summit of Cheyenne ridge. This cell development is also consistent with convective cloud modeling studies (Weisman and Klemp, 1982) which suggest that new convection is more likely to form on the portion of an arc line that is propagating in the direction of the low-level ambient shear vector. Under these conditions, air parcels are lifted more vigorously along the gust front and are more likely to reach their level of free convection.

The apparent role of the propagating arc line in initiating the new convection that subsequently produced severe weather has important ramifications for the forecasting and warning of severe storms. Our analysis suggests that areas of 25,000 km^2 can be identified several hours in advance as potential regions of severe thunderstorm activity. However, the analysis also suggests that processes on the cloud scale determine the ultimate precise location of the severe thunderstorms within the larger threat area. It therefore appears that even with continuous monitoring of cloud-scale developments, lead times for detailed warnings of severe thunderstorm development are limited to less than an hour.

The evolution of the multicellular cloud system into the supercell structure is of considerable interest. It is not clear whether the formation of the supercell over a period of an hour was a natural evolution from a multicellular embryo and independent of a changing hodograph, or whether the approaching short-wave trough eventually produced a shear profile more disposed to supercell formation than that which existed during the earlier phase of storm formation. Unfortunately, the observations required to answer this question with certainty do not exist. Numerical cloud model simulations typically indicate a time period of 1 to $1\frac{1}{2}$ h to generate a supercell from initial convection. On the other hand, the Platteville profiler data suggest that slight changes in the wind field below 5 km may have preceded the trough passage; such changes might have had a role in transforming the multicellular system to a supercell.

It appears that the transition from a multicellular system to a rotating supercell was instrumental in changing the motion of the storm. In the storm's multicellular stage, cells were drifting slowly northward, consistent with the pressure-weighted vector mean wind of the storm environment, which was computed to be from 190° at 5.5 m s^{-1}. After the transition to a rotating supercell, the storm became quasi-stationary for a period before beginning a slow southeastward drift that appeared to quicken with the arrival of the middle-level trough. Evidence presented here suggests that propagation transverse to the mean wind shear largely counteracted effects of the pressure-weighted vector mean wind to anchor the storm.

The results of this study have important implications for the eastern foothills of the Rocky Mountains and the adjacent high plains. Over this area, deep convection frequently occurs when the low-level jet is from the east and moist air from the Great Plains is carried westward into the foothills and adjacent high plains. If midtropospheric winds are also weak and southerly, it appears that wind shear sufficient to produce a supercell storm can be generated simultaneously with a pressure-weighted mean vector wind that gives little or no eastward motion relative to the ground. This contrasts with the normal wind configuration for supercells east of the Rocky Mountain lee trough, where southerly low-level jetstreams generally produce relatively fast-moving supercells. The eastern foothills and adjacent high plains from eastern New Mexico and west Texas north to Montana therefore seem particularly vulnerable to these slow-moving or quasi-stationary supercell storms.

ACKNOWLEDGMENTS

We wish to acknowledge Mr. William T. Parker, Meteorologist in Charge of the Cheyenne WSFO, for providing data and information used in this study. Robert T. Glancy and John A. Daseler of the Cheyenne WSFO also provided information and helpful discussions about the storm. John Marwitz provided a series of storm photographs taken from Laramie, Wyoming, as well as valuable comments concerning storm evolution. Timothy Kittel and Nancy Cobb graciously supplied additional sets of storm pictures. We are grateful to PROFS for supplying Doppler radar and satellite data used in the analysis. Larry Wirth kindly provided data and valuable comments concerning radar observations taken at the National Weather Service office in Alliance, Nebraska. James Bresch provided Colorado mountain wind data obtained during this episode by the Rocky Mountain Peaks Experiment. We thank Morris L. Weisman and Richard Rotunno for very helpful discussions concerning storm genesis and evolution, and John Brown for many helpful comments.

REFERENCES

Barnes, S. L., 1985: Omega diagnostics as a supplement to LFM/MOS guidance in weakly forced convective situations. Mon. Wea. Rev., 113: 2122-2141.

Bellville, J. D., G. A. Johnson, A. R. Moller, and J. D. Ward, 1980: A synoptic and mesoscale analysis of the Palo Duro Canyon flash flood and associated severe weather. Preprints, Second Conference on Flash Floods, Atlanta, American Meteorological Society, Boston, 30-37.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. J. Atmos. Sci., 21: 634-639.

Dennis, A. S., R. A. Schleusener, J. H. Hirsch, and A. Koscielski, 1973: Meteorology of the Black Hills Flood of 1972. Institute of Atmos. Sci., Report 73-4, South Dakota School of Mines and Technology, Rapid City, 41 pp.

Hoskins, B. J., 1975: The geostrophic momentum approximation and the semi-geostrophic equations. J. Atmos. Sci., 32: 233-242.

Lemon, L. R., 1980: Severe Thunderstorm Radar Identification Techniques and Warning Criteria. NOAA Tech. Memo. NWS NSSFC-3, 60 pp.

Lilly, D. K., 1986a: The structure, energetics and propagation of rotating convective storms. Part I: Energy exchange with the mean flow. J. Atmos Sci., 43: 113-125.

Lilly, D. K., 1986b: The structure, energetics and propagation of rotating convective storms. Part II: Helicity and storm stabilization. J. Atmos. Sci., 43: 126-140.

Maddox, R. A., F. Caracena, L. R. Hoxit, and C. F. Chappell, 1977: Meteorological aspects of the Big Thompson flash flood of 31 July 1976. NOAA TR ERL 388-APCL 41, 84 pp.

Maddox, R. A., L. R. Hoxit, C. F. Chappell, and F. Caracena, 1978: Comparison of meteorological aspects of the Big Thompson and Rapid City flash floods. Mon. Wea. Rev., 106: 375-389.

Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. J. Atmos. Sci., 42: 271-292.

Szoke, E. J., M. L. Weisman, J. M. Brown, F. Caracena, and T. W. Schlatter, 1984: A subsynoptic analysis of the Denver tornadoes of 3 June 1981. Mon. Wea. Rev., 112: 790-808.

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. Mon. Wea. Rev., 110: 504-520.

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