Comparison of Meteorological Aspects of the Big Thompson and Rapid City Flash Floods

ROBERT A. MADDOX, LEE R. HOXIT, CHARLES F. CHAPPELL AND FERNANDO CARACENA

Atmospheric Physics and Chemistry Laboratory, NOAA, Boulder, Colo. 80302

(Manuscript received 10 November 1977, in final form 16 December 1977)

ABSTRACT

Analyses and descriptions of the meteorological conditions that produced devastating flash floods in the Big Thompson Canyon on 31 July 1976 and in the Black Hills on 9 June 1972 are presented. The storms developed when strong low-level easterly winds pushed moist, conditionally unstable air masses upslope into elevated, mountainous terrain. Orographic uplift released the convective instability and light winds aloft allowed the storm complexes to remain nearly stationary. Meteorological conditions that produced these flash floods were found to have been very similar. A set of meteorological features is defined for the purpose of identifying the potential for this type flash flood along the eastern slopes of the Rocky Mountains.

1. Introduction

The deaths, damage and human suffering inflicted by the recent Johnstown, Pa., flood have once again emphasized the importance of effective flash flood prediction, detection and warning systems. Cressman (1977) recently stated that flash floods have become the major natural disaster warning problem in the United States. He also noted that:

> "During the 1970's the average annual death toll from flash floods has risen to around 200. This is more than double the rate of the 1960's and more than triple the rate of the 1940's. A single flood such as the ones at Rapid City, S. Dak., in 1972, and Big Thompson Canyon, Colo., in 1976 can claim 100–200 lives. Property damages of $100 million are normal for a major flash flood, and the economic life of a community hit by one is disrupted for months as industries recover from the sudden losses."

Flash floods are distinguished from general river flooding by the very rapid rise in the runoff water level with the damaging flood usually occurring within hours of the causative rainfall. The area affected is limited and is most often restricted to a single stream or drainage basin (Williams *et al.*, 1972). The short time interval between the occurrence of heavy rains and the actual flood event requires an advance preparedness effort in addition to rapid responses by local agencies (i.e., National Weather Service, Civil Defense, etc.) to produce effective warnings. The problem is in many ways similar to that of tornado prediction, detection and warning.

Rainfalls which result in flash floods are usually produced by intense convective storms, although the causative and organizing features may vary considerably. Tropical disturbances may interact with extratropical weather systems and/or terrain features to produce regions of intense local rains (Schlegel, 1976; Williams *et al.*, 1972). Slow-moving thunderstorms often produce localized heavy rains over the western United States during summer and fall months and destructive flash floods occasionally result (Williams, 1976; Randerson, 1976). A thunderstorm that moves slowly down a drainage basin may produce a spectacular "wall of water" such as that which struck El Dorado Canyon, Nev. (NOAA-WR, 1974).

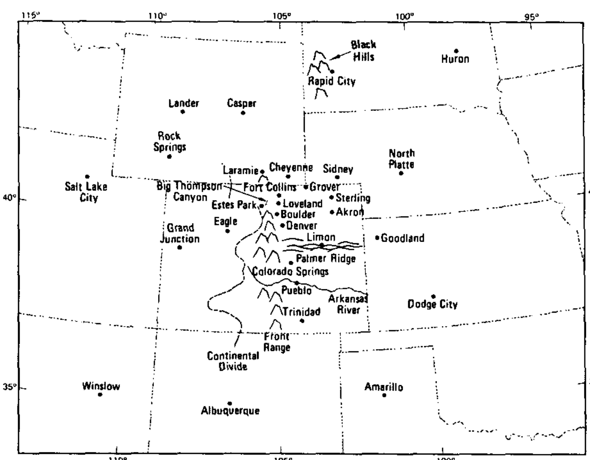

FIG. 1. Locations and topographical features in Colorado and surrounding states.

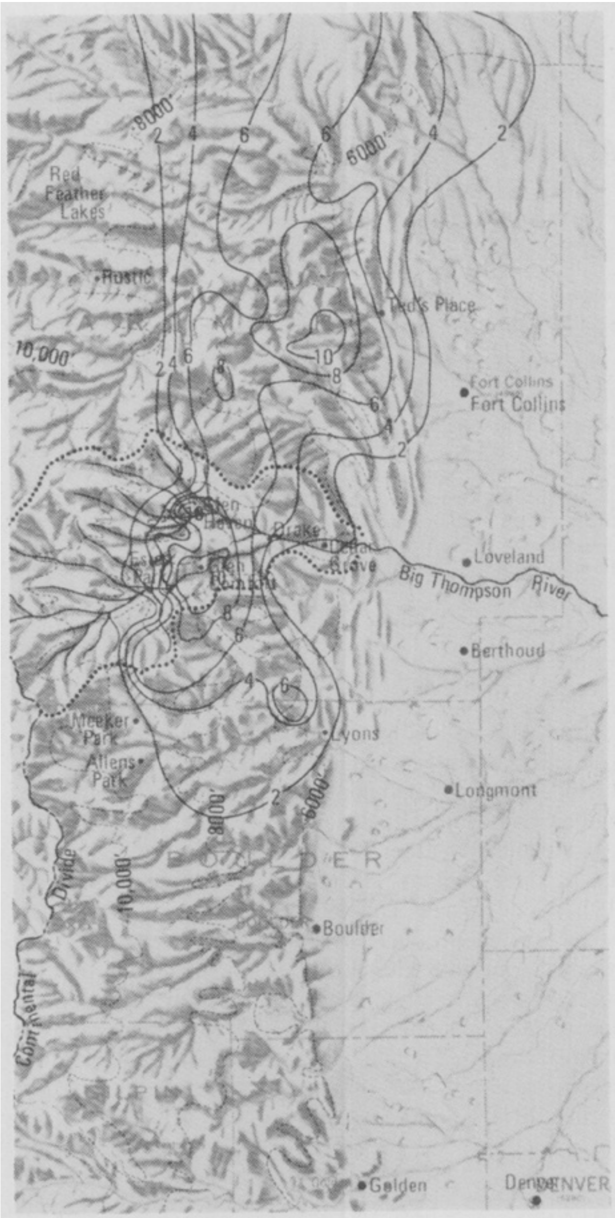

FIG. 2. Big Thompson and North Fork of the Big Thompson drainages (dotted line). Cumulative rainfall isohyets (black lines) are shown. Terrain contours (ft ASL) are dashed. The precipitation summary and isohyetal map were prepared by the National Weather Service Central Region Headquarters in cooperation with other Federal Agencies.

Organized mesoscale thunderstorm systems can produce large precipitation accumulations due to persistent storms and/or repeated cell development over a small area (Fujita *et al.*, 1977; Mogil and Groper, 1976; Merritt *et al.*, 1974; Sourbeer and Gentry, 1961). Orographic lifting may trigger convective storms along mountain barriers and intense flash flooding can result (Williams *et al.*, 1972; Schroeder, 1977).

This last type of flash flood was of particular interest in this study since destructive flash floods occurred in the Black Hills of South Dakota and in Colorado's Big Thompson Canyon during the past few years. This paper compares the meteorological conditions which produced these east slope floods and summarizes their common features. A more detailed analysis of Big Thompson meteorological conditions is presented by Maddox *et al.* (1977), and a comprehensive study of Rapid City conditions may be found in Dennis *et al.* (1973).

2. The flood events

During the evening hours of 31 July 1976, a destructive flash flood rushed through the Big Thompson Canyon west of Loveland, Colo. U. S. Highway 34, the primary route into Estes Park and Rocky Mountain National Park, parallels the river. The canyon had been extensively developed with businesses, motels and campgrounds located along the scenic river bank. Larimer County officials estimated that between 2500 and 3500 persons were in the canyon when the flood occurred (NOAA, 1976), and the toll was heavy; at least 139 people were killed, and property damage of about $35.5 million occurred.

The storm produced very heavy rains in a narrow band along the Front Range from the Big Thompson drainage northward into Wyoming. Maximum amounts exceeded 12 inches with most of the precipitation in the Big Thompson drainage falling during the period from 0030 to 0430 GMT. (GMT is converted to Mountain Daylight Time by subtracting 6 h.) Sig-

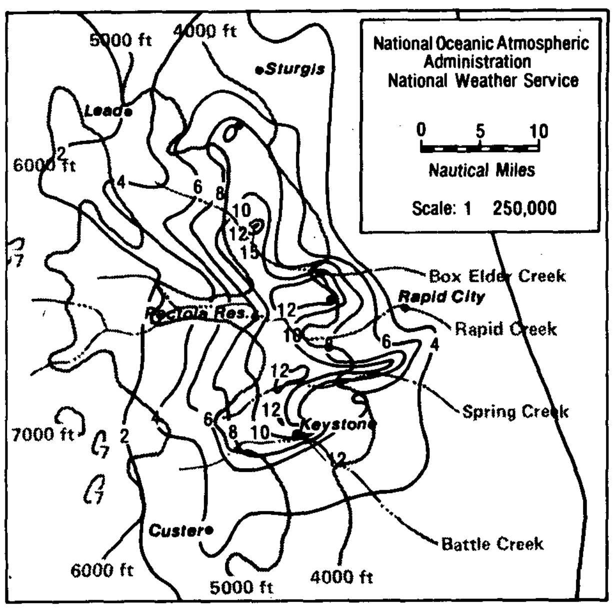

FIG. 3. Map of the Rapid City and Black Hills area affected by flooding. Cumulative rainfall isohyets (heavy lines) are shown. Terrain contours (1000's of feet AGL) are lighter. The precipitation summary and isohyetal map were prepared by the National Weather Service Central Region Headquarters in cooperation with other Federal Agencies.

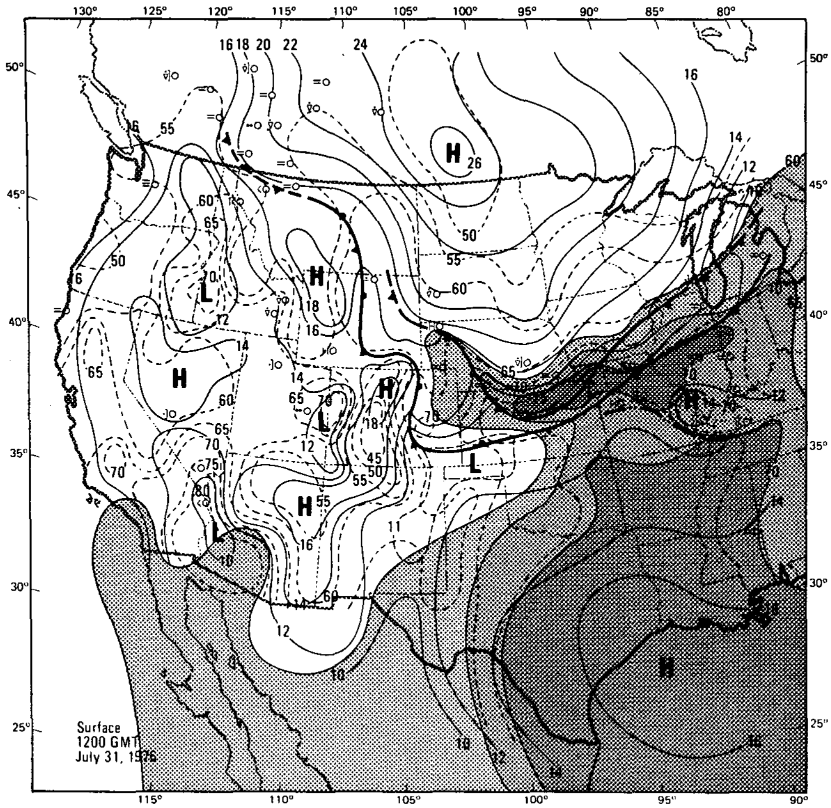

FIG. 4a. Surface analysis for 1200 GMT 31 July 1976. Frontal positions, pressure centers and isobars for 2 mb intervals (12 = 1012) are solid lines. Isotherms for 5°F intervals are dashed lines. Dew-points ≥60°F are analyzed at 5°F intervals with the high dew-point region shaded.

nificant flooding and damage occurred in Colorado on the Big Thompson and the North Fork of the Big Thompson, and on other drainage basins along the Front Range from the Big Thompson north to the Wyoming border. Flash flooding was also reported over areas west and northwest of Cheyenne, Wyo.

Fig. 1 shows Colorado and surrounding states and identified landmarks and towns that are referred to in the paper. The Big Thompson drainage and cumulative rainfall isohyets are depicted in Fig. 2. The precipitation summary covers the period 31 July–2 August 1976.

Slightly more than four years earlier, a similar event occurred in the Black Hills of South Dakota. This flash flood killed at least 236 persons and caused damage within Rapid City of more than $100 million (Thompson, 1972). The Rapid City storm complex produced very heavy rains (Fig. 3) in a narrow north-to-south band along the eastern slopes of the Black Hills. The precipitation summary is for 9 and 10 June 1972. Maximum amounts reached 15 inches with much of the precipitation over the Rapid Creek drainage falling during the period from 0000 to 0400 GMT 10 June 1972. Significant flooding also occurred on Box Elder, Spring and Battle Creeks and much of the town of Keystone on Battle Creek was destroyed.

3. Meteorological conditions prior to storm development

a. *Analyses at 1200 GMT 31 July 1976 and 9 June 1972*

Surface and 500 mb analyses are shown in Figs. 4–7 for 1200 GMT on the day of the floods. Fig. 4 presents conditions for the Big Thompson storm. Important surface features included a strong polar high pressure area centered over southern Canada, and a weak low pressure area located near Grand Junction in western Colorado. A double frontal structure at the periphery of the polar air mass stretched from the Great Lakes through Kansas and Colorado northward across central Montana. The leading front was characterized by wind shifts and a pressure trough, whereas the trailing front was marked by a less pronounced pressure trough, relatively strong temperature gradients and an increase in wind speed. Thermal packing was most pronounced along and to the rear of the trailing front across Kansas and Nebraska.

Dew-point temperatures were high with values of 60°F extending northwestward from Kansas into Colorado and Nebraska. A band of very moist air lay just to the rear of the trailing front where dew-points of 65°F or greater had moved into south-

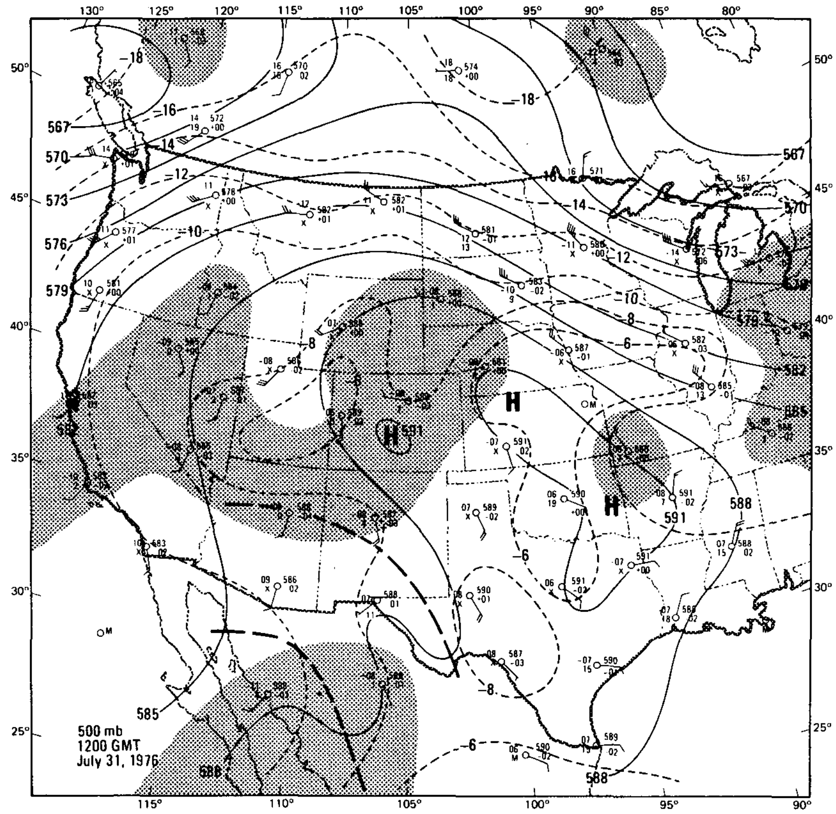

FIG. 4b. 500 mb analysis for 1200 GMT 31 July 1976. Height contours (drawn for every 30 m, 570=5700 m) and circulation centers are solid, short-wave troughs and isotherms for 2°C intervals are dashed. Regions where $T-T_d \leqslant 6$°C are shaded to indicate moist conditions.

western Nebraska. Early morning shower and thundershower activity was occurring from Missouri to western South Dakota and also over much of the intermountain west.

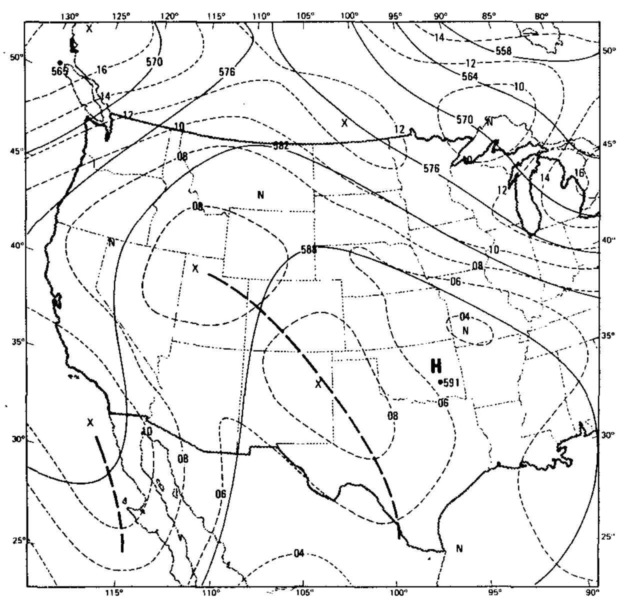

FIG. 5. NMC-LFM 12 h forecast of 500 mb heights (solid) and vorticity (dashed), valid 0000 GMT 1 August 1976.

Upper air features were dominated by a large, negatively tilted or "bentback" ridge (the ridge line sloped from SSE to NNW), which extended from southern Texas to west-central Canada. A closed high was present over the Central Plains (see Fig. 4b). Moist conditions were present over the intermountain West and eastern slopes of the Rockies from 700 through 300 mb.

Two weak 500 mb short-wave troughs, one over Mexico and another over Arizona and New Mexico, were imbedded in the southerly flow west of the ridge line. A broad area of falling heights with a weak fall center over the Four Corners area was associated with these troughs. A small, closed anticyclonic circulation over the Colorado mountains produced westerly winds at 500 mb over Denver, while winds were southerly at Grand Junction.

The NMC-LFM vorticity forecast (Fig. 5) valid at 0000 GMT 1 August indicated that the "bentback" ridge line would move slightly eastward during the day, allowing weak southerly flow to become established over the Front Range. A single short-wave trough was forecast to extend from southeastern Idaho to west Texas. Weak positive vorticity advection was forecast to occur over most of the Rocky Mountain region during the day, which would contribute to further destabilization of the air mass.

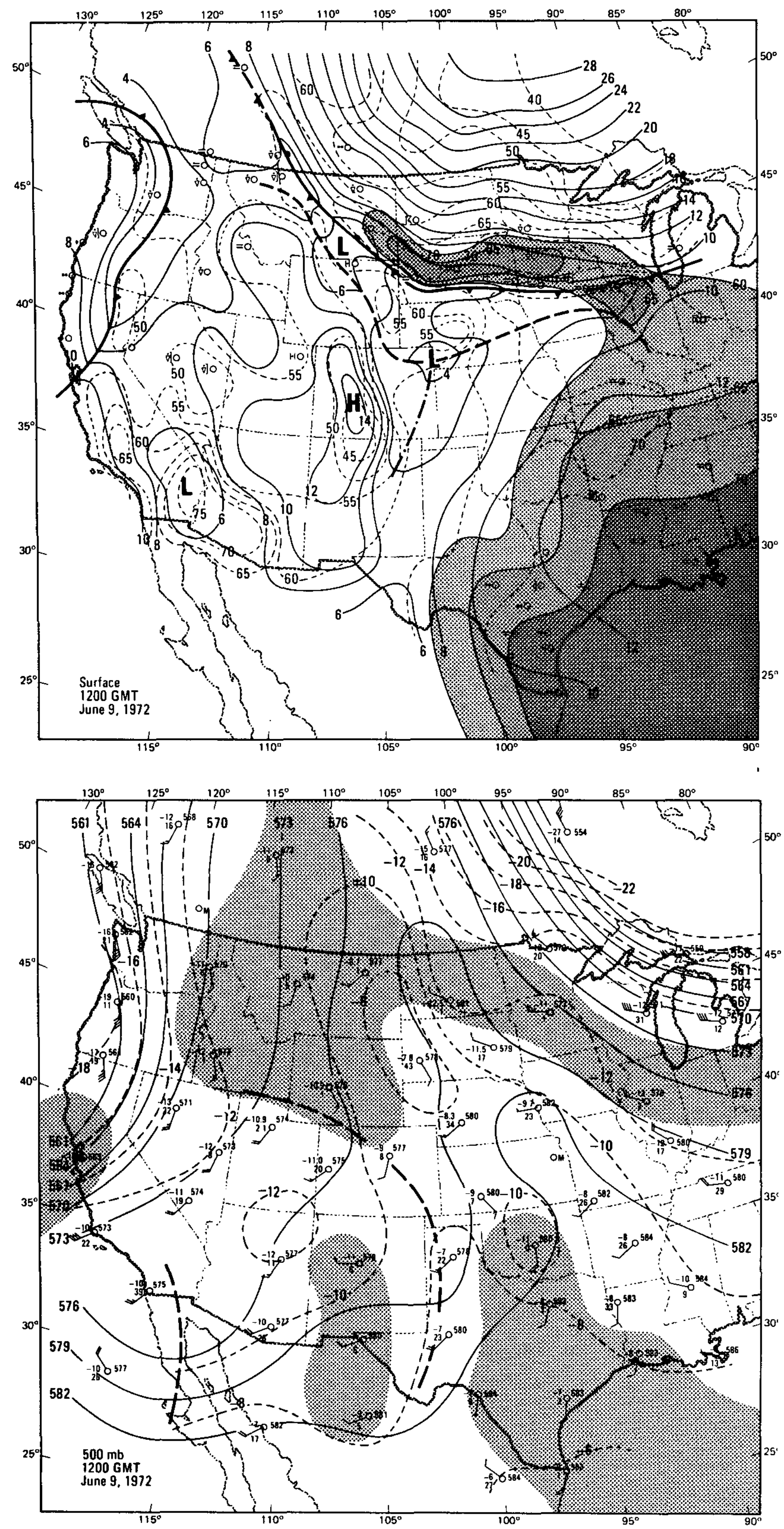

FIG. 6. Surface (a) and 500 mb (b) analyses for 1200 GMT 9 June 1972. Refer to legend of Fig. 4 for details.

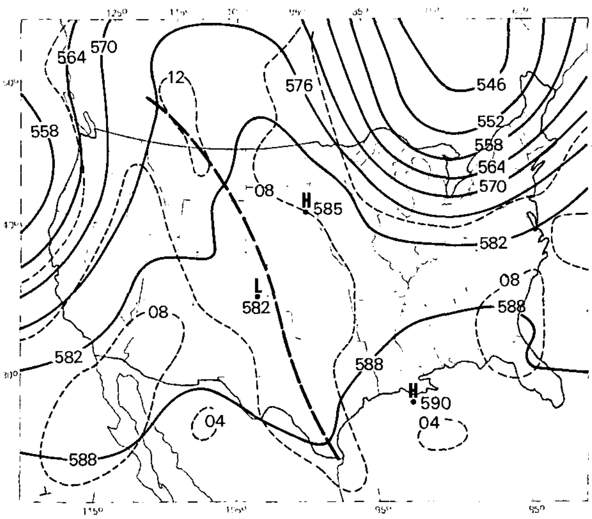

FIG. 7. NMC-LFM 12 h forecast of 500 mb heights (solid) and vorticity (dashed) valid 0000 GMT 10 June 1972.

Rapid City surface conditions (Fig. 6a) were very similar with a polar front lying just south of the Rapid City area. A band of very moist air lay just to the rear of this front and stretched from southern Minnesota to southeastern Montana. Lower dew points were indicated south and west of the front. Although only one front was analyzed, notice that the isotherm analysis showed the leading edge of the region of strong temperature gradient to be located 150–300 km north of the frontal position. The dashed line represents a wind shift line.

At 500 mb (Fig. 6b) a large-amplitude, negatively tilted ridge was again the dominant feature. The ridge line stretched from Louisiana north-northwestward across central Canada and was located 200–300 km east of the Rapid City area. A weak short-wave trough, that was moving northward up the back of the ridge, was located to the south and southwest. Light southeasterly winds were indicated over western South Dakota and abundant moisture was present ahead of the short wave.

The NMC-LFM 12 h vorticity forecast (Fig. 7) showed that the "bentback" ridge line would be located just east of the Black Hills at 0000 GMT. Weak positive vorticity advection was indicated over the western Dakotas as the short-wave trough approached from the south-southwest.

b. Upper air soundings prior to storm development

The 1200 GMT Denver upper air sounding taken on 31 July 1976 is shown in Fig. 8a. Denver is located approximately 80 km south-southeast of the Big Thompson flood area. The sounding was very moist below a temperature inversion at 670 mb, and winds were generally light and variable. The Lifted Index (LI) was computed for a lifted parcel with mean thermodynamic characteristics of the lowest 100 mb layer and was −1; however, the height (530 mb) of the level of free convection (LFC) indicated considerable lifting and/or heating would be needed to initiate deep convection. The high moisture values were the most unusual feature of the sounding. Precipitable water contents of 0.67 inches in the lowest 150 mb layer and 1.00 inch in the layer from the surface to 500 mb were approximately 50% above Denver July means (Lott, 1976) of 0.40 and 0.69 inches, respectively. A low overcast at 0.37 km AGL was reported at Denver at sounding time.

A 1920 GMT upper air sounding was taken at Sterling, Colo., during operations of the National Hail Research Experiment (NHRE). This sounding (Fig. 8b) was taken about 40 km to the rear of the trailing cold front and exhibited important differences from the Denver morning sounding. The LI was a very unstable −4, and the LFC was lower, 640 mb. Precipitable water contents of 0.78 inches in the lowest 150 mb layer and of 1.31 inches in the surface-to-500 mb layer were almost double the July means for Denver. Winds above a temperature inversion (considered to be of frontal origin) at 720 mb were westerly at 10–20 kt, indicating that Sterling was very near the upper ridge line. Easterly low-level flow of 10–15 kt was evident. The Sterling sonde had sampled the air mass just behind the trailing front and found it to be conditionally very unstable with an unusually high moisture content. This air mass was moving westward and southwestward toward the Colorado Front Range at 15–20 kt and required lifting of ~140 mb to release its instability.

The 1200 GMT sounding taken at Rapid City on 9 June 1972 is shown in Fig. 9a. The sounding showed a shallow moist layer near the surface which was capped by a strong temperature inversion at 860 mb (also of frontal origin) with very dry conditions above. Winds aloft were southerly to easterly and generally less than 15 kt. The LI was a very stable +6; however, because of Rapid City's proximity to the frontal boundary, the sounding was not at all representative of conditions to the east.

The 1200 GMT Huron upper air sounding (Fig. 9b) taken approximately 390 km east-northeast of Rapid City and about 100 km north of the polar front was much different. Temperature, moisture and wind data indicated that the cool, moist air extended upward to 780 mb. Easterly winds within this air mass peaked at 25 kt with light westerly winds (≤10 kt) extending from 780 mb to the tropopause. The air mass was very unstable (LI = −7), but it required lifting from 850 mb (LCL) to 700 mb (LFC) to release the instability. As in the Sterling sounding moisture contents were extremely high. Precipitable water contents of 0.80 inches in the lowest 150 mb layer and of 1.32 inches in the surface-to-500 mb layer were nearly

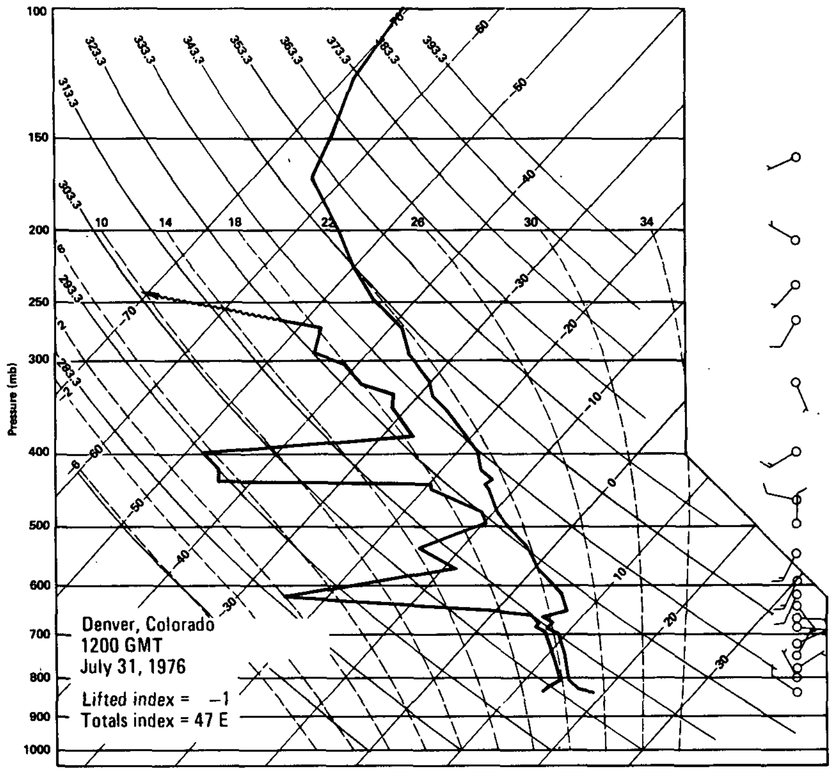

FIG. 8a. Skew $T/\log P$ plot of 1200 GMT 31 July 1976 Denver upper air sounding. Wind speeds are in knots; full barb = 10 kt, half-barb = 5 kt.

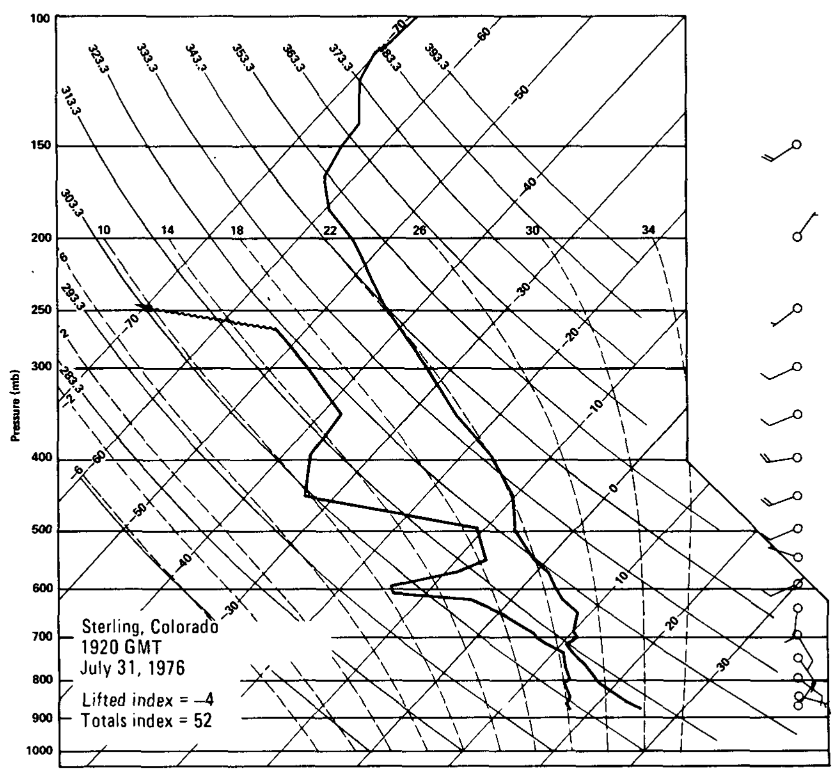

FIG. 8b. Skew $T/\log P$ plot of 1920 GMT 31 July 1976 Sterling, Colo., upper air sounding.

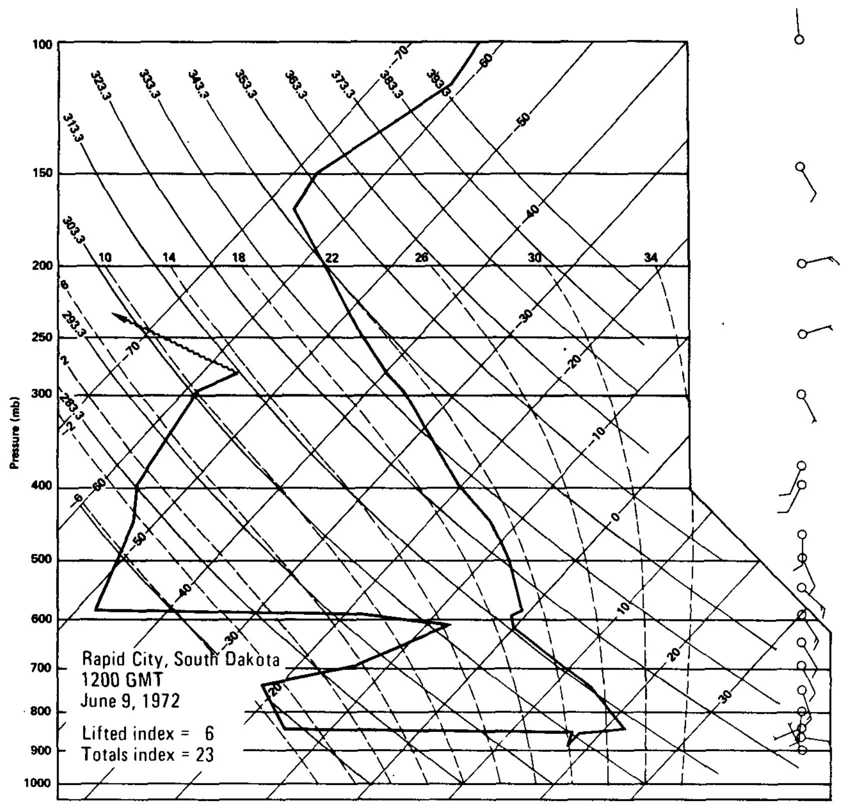

FIG. 9a. Skew $T/\log P$ plot of 1200 GMT 9 June 1972 Rapid City upper air sounding.

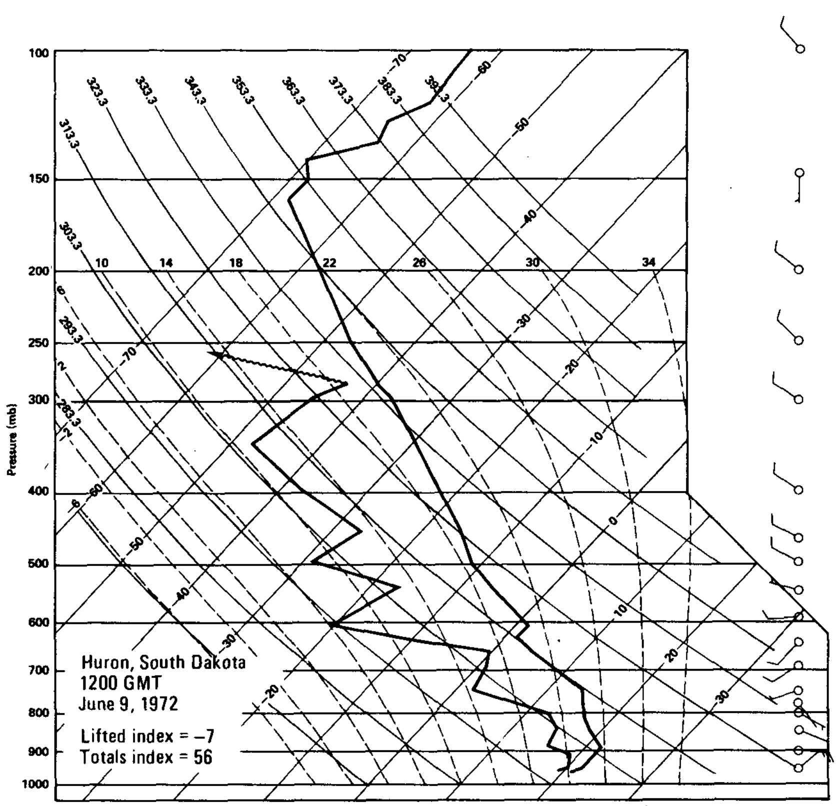

FIG. 9b. Skew $T/\log P$ plot of 1200 GMT 9 June 1972 Huron, S.D., upper air sounding.

twice the Rapid City June means of 0.41 and 0.71 inches.

In both the Rapid City and Big Thompson cases upper air soundings taken to the east-northeast were more representative of the air mass in which intense storms were triggered later in the day. Both the Huron and Sterling soundings indicated that the cooler air masses trailing the fronts were conditionally very unstable. Temperature inversions capped the unstable, moist boundary layer and almost 150 mb of lifting was needed to release the instability.

Sterling soundings (Fig. 10) that were taken on 31 July for the Big Thompson case demonstrate the changing moisture and stability characteristics of the air masses ahead of, immediately behind, and well behind the trailing front. Of most interest are the changes that occurred within the lowest 2 km. The 1340 GMT sounding showed a layer of high θ_e values very near the surface, but θ_e decreased rapidly within the lowest kilometer. Although Sterling was well within the cool air mass behind the leading front, the moist layer was actually very shallow. The 1920 GMT sounding indicated a dramatic increase in θ_e throughout a layer extending from the surface to almost 4 km. Values of θ_e at the surface had increased from 343 to 353 K, and θ_e at 1 km AGL had increased from 334 to 345 K. During the same period the surface temperature had increased only 5.9°C, while the temperature at 1 km AGL had actually decreased 0.9°C. The large changes in θ_e were therefore primarily due to the arrival of higher moisture content air behind the trailing front. The zone characterized by high θ_e and a deep moist layer was approximately 100 km in width. The 2202 GMT sounding showed a decrease of 4 K in mean θ_e for the lowest kilometer.

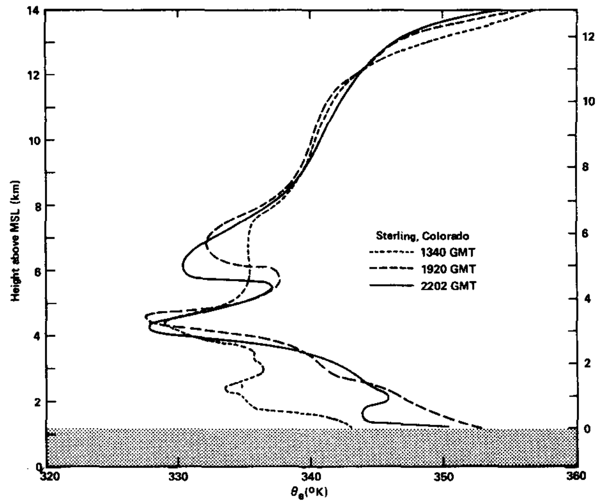

FIG. 10. Height profiles of equivalent potential temperature (θ_e) for the three Sterling, Colo., upper air soundings taken on 31 July 1976.

4. Meteorological conditions at 0000 GMT

a. Analyses at 0000 GMT 1 August 1976 and 10 June 1972

Surface and 500 mb analyses are shown in Figs. 11 and 14 for 0000 GMT. The period of very intense rains began shortly after 0000 GMT in both cases. Conditions associated with the Big Thompson storm complex are presented in Figs. 11–13.

By 0000 GMT the trailing front had overtaken and reinforced the leading front, except in south central Colorado. In this region the leading front had become diffuse and was analyzed as undergoing frontolysis. The low pressure in western Colorado had deepened to 1005 mb and was located northwest of Eagle. Surface pressures had remained nearly constant along the Front Range, and had risen 1–3 mb over southwestern Nebraska, northwestern Kansas and northeastern Colorado. A 1200 GMT pressure difference of 2.9 mb between Grand Junction and Sidney, Nebr., had increased to 10.5 mb by evening. Twelve-hour changes in the 850–500 mb thickness indicated that the strengthening of the easterly pressure gradient was occurring through a large depth of the troposphere. In response to this increasing pressure gradient, low-level easterly flow had maximized in a broad band from central Kansas westward to northeastern Colorado and eastern Wyoming. Surface reports included steady winds at 25 kt at Akron, gusts to 21 kt at Ft. Collins and gusts to 24 kt at Denver. This strong moist flow was oriented nearly normal to the Front Range.

Surface observations, and the radar and satellite data shown in Figs. 12a and 12b, indicated widespread mountain thunderstorm activity. A large squall line stretched from northern Nevada through southern Idaho to southeastern Utah. A line of strong and visually impressive thunderstorms stretched from Colorado to southern Missouri along and behind the polar front. Even though tops on several of these storms grew to over 15.3 km MSL (50 000 ft.), no severe weather was reported with them. A large area of thunderstorms had developed over east central Wyoming to the rear of the front, and the first cells in the area of the Big Thompson watershed were just beginning to develop over the mountains southwest of Ft. Collins. Note that the GOES satellite photograph depicts the mesoscale distributions of active thunderstorms much more accurately than does the generalized radar summary chart. The smaller cumulus clouds over northern Kansas, southwestern Nebraska and northeastern Colorado had dissipated as boundary layer cooling began.

Upper air analyses indicated that the large, negatively tilted ridge had intensified and developed north-westward during the day. The cutoff high within the ridge had drifted slightly southward over the central Plains and the ridge line extended from

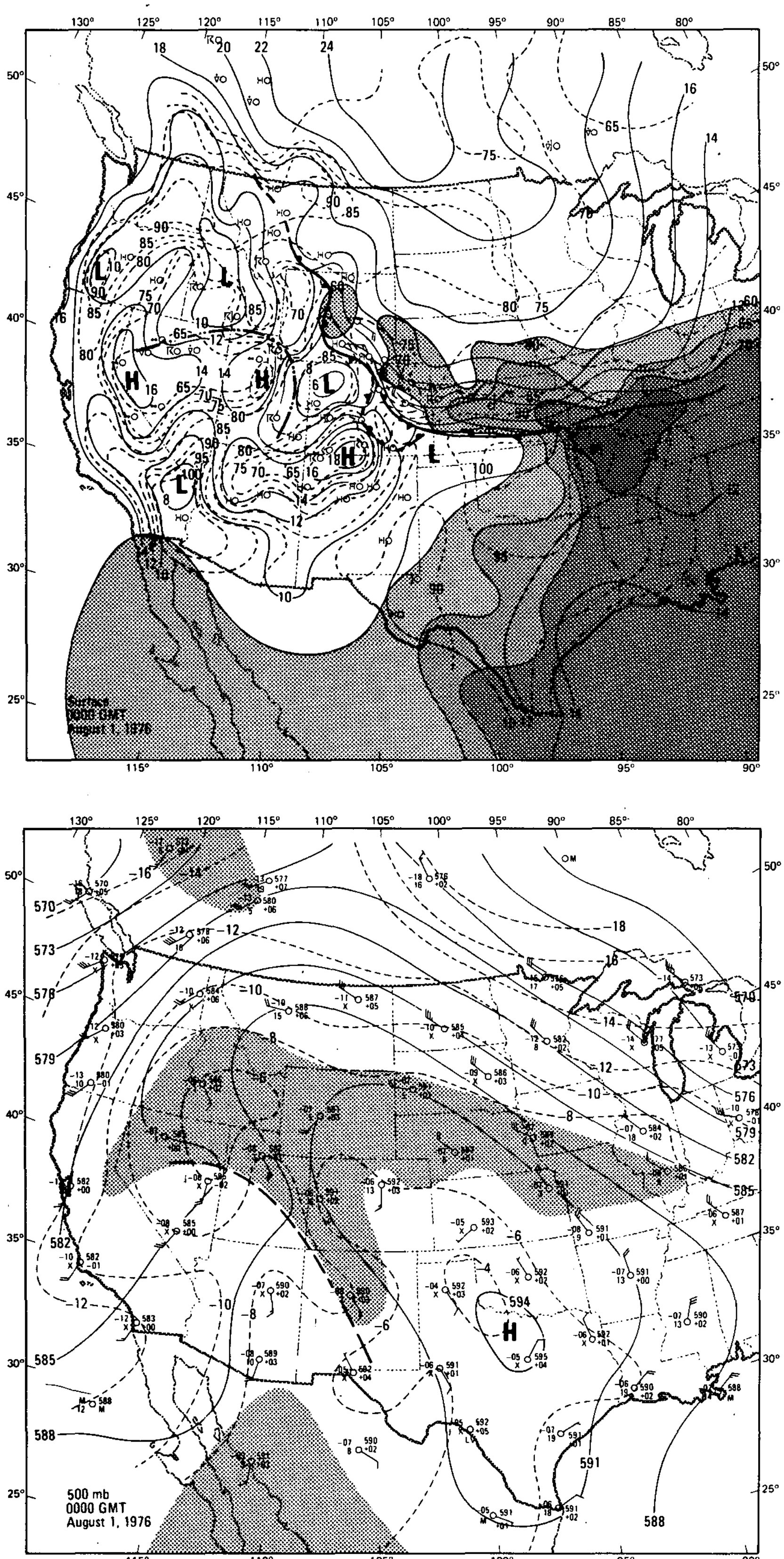

FIG. 11. Surface (a) and 500 mb (b) analyses for 0000 GMT 1 August 1976. Refer to the legend of Fig. 4 for details.

western Kansas to central Montana. Warm air aloft had suppressed development of deep convection over the plains south of the surface front. Winds aloft over eastern Colorado were south to south-southeasterly at only 10–25 kt.

The 0000 GMT 500 mb analysis (Fig. 11b) showed that the two short waves found on the 1200 GMT chart had merged and a single trough now extended in an arc from central Nevada to New Mexico. The position and northward movement of this short wave suggests that falling pressures in western Colorado were probably caused by a combination of dynamical effects and afternoon heating. High moisture content was evident ahead of the trough.

The short-wave trough was clearly reflected on the 0000 GMT vorticity analysis (Fig. 13) with positive vorticity advection indicated over a broad area from northwest Texas to Idaho and northern Nevada. Comparison with Fig. 5 shows that the analyzed position of the short wave agreed reasonably well with the forecast although the feature was more intense than predicted. The Big Thompson storm was developing in a region of minimum vorticity and weak positive vorticity advection. The active squall line in Nevada and Utah was just ahead of the northward moving short wave.

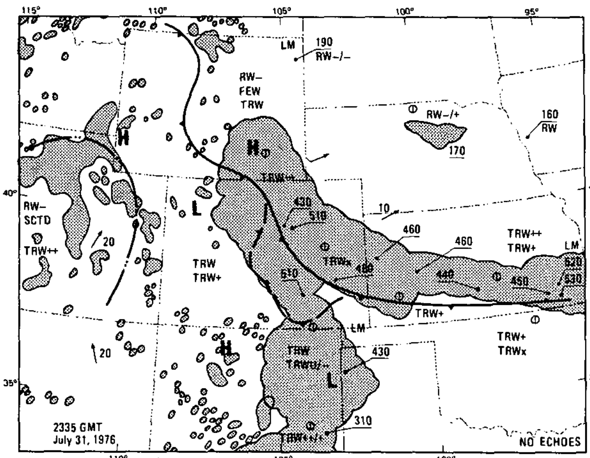

FIG. 12a. Radar summary chart for 2335 GMT 31 July 1976.

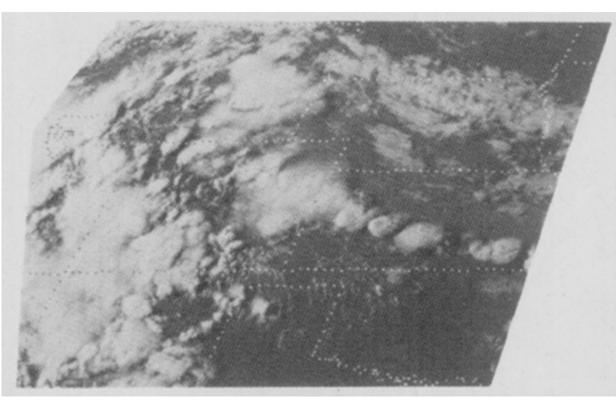

FIG. 12b. GOES-I satellite photograph for 0000 GMT 1 August 1976.

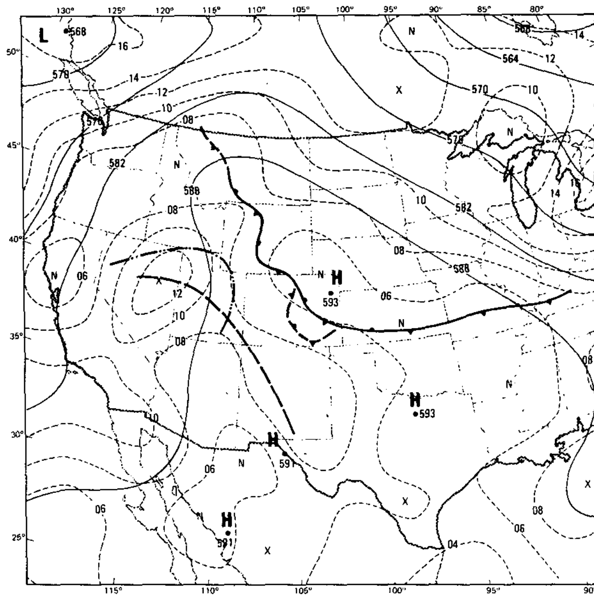

FIG. 13. NMC-LFM vorticity analysis (dashed) for 0000 GMT 1 August 1976. Synoptic surface analysis and 500 mb height analysis are solid. Positions of the important 500 mb short wave and squall line are also shown.

Surface and 500 mb analyses for the Rapid City situation are presented in Fig. 14. The surface analysis indicated that the polar front stretched from central Illinois westward across central Nebraska and then northwestward through central Montana. The front was just south of the Black Hills in the extreme southwestern corner of South Dakota. Surface pressures were lower south and west of the Rapid City area and surface easterly winds had increased to 20–30 kt across most of South Dakota. The area of high dew points had broken off from the moist air mass south of the front over the central Mississippi Valley and a narrow zone of moist air was concentrated north of the polar front from western Iowa northwestward across Montana. Convective activity in the hotter, drier airmass to the south and west of the Rapid City was organizing into a weak squall line across eastern Wyoming and eastern Colorado.

At 500 mb (Fig. 14b) the weak short-wave trough was approaching from the south and west and the movement and orientation of the short wave had apparently helped to maintain lower pressure west of the Black Hills area. Winds were southeasterly over western South Dakota and the ridge line was located between Rapid City and Huron. The 0000 GMT LFM vorticity analysis (Fig. 15) was very similar to that for the Big Thompson case. The Black Hills storm developed in a region of weak positive advec-

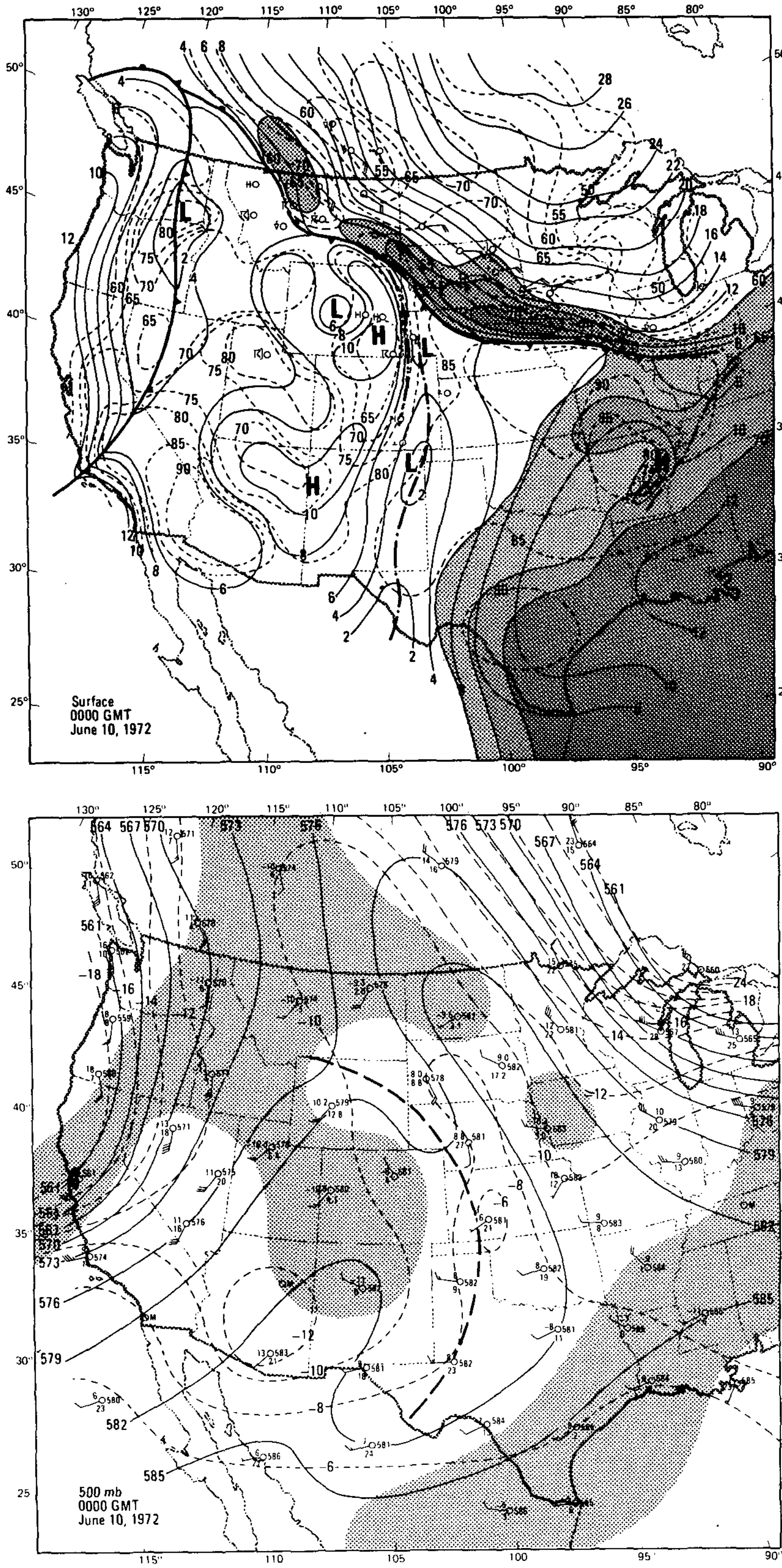

FIG. 14. Surface (a) and 500 mb (b) analyses for 0000 GMT 10 June 1972. Refer to legend of Fig. 4 for details.

tion with convection to the south and west organized along the weak short wave.

b. Upper air soundings in the storm environment

Upper air soundings considered representative of the near-storm environments are presented in Fig. 16. The Loveland sounding (Fig. 16a) was constructed making use of various types of data available for 0000 GMT on 1 August 1976. The reader should refer to Maddox *et al.* (1977) for specific details. The LI was -6 and the mean vapor mixing ratio below the temperature inversion was 14.8 g kg^{-1}. The LCL was at 730 mb ($\sim$1.1 km AGL), which agrees with observed low cloud heights at Ft. Collins. An additional 80 mb of lift was necessary to bring this air to its LFC.

The Rapid City sounding at 0000 GMT 10 June 1972 (Fig. 16b) was considerably different than the sounding taken 12 h earlier. Precipitable water for the lowest 150 mb layer had increased from 0.28 inches to 0.76 inches, and from 0.42 to 1.32 inches for the surface-to-500 mb layer. Rapid City dew point analyses presented by Schwarz *et al.* (1975) showed little change at the surface during the 12 h preceding the flood; however, the moisture content of the lowest 150 mb layer had almost tripled during the same period. The LI at 0000 GMT was -5 and winds in the lowest 1–2 km were now strong easterly; winds at higher levels were light southeasterly. Winds became light southwesterly above 250 mb. The Rapid City sonde sampled active convection (Dennis *et al.*, 1973) and thus did not exhibit the temperature inversion.

Table 1 compares the Rapid City and Loveland soundings with conditions associated with severe Central Plains' thunderstorms (storms producing large hail and/or damaging winds and/or tornadoes). LI's and moisture contents are comparable; however, the wind fields are dramatically different. The wind veers with height in both types of soundings, but the heavy rain soundings are characterized by strong easterly winds near the surface and light southerly winds aloft. This "reverse" shear contrasts markedly with the strongly sheared severe storm environment. Caracena *et al.* (1977) have found that cloud microphysical processes, and the physical structure of the heavy rain storm in "reverse" shear, are much different from those associated with the usual severe thunderstorm and that these differences help to produce a highly efficient precipitation system.

5. Summary

Large thunderstorm complexes dropped 10–15 inches of rain in the foothills west of Loveland, Colo., and west of Rapid City, S. Dak., during the evening hours of 31 July 1976 and 9 June 1972, respectively. Resultant flash floods devastated the Big Thompson Canyon and much of Rapid City claiming at least 375 lives and producing heavy property damage.

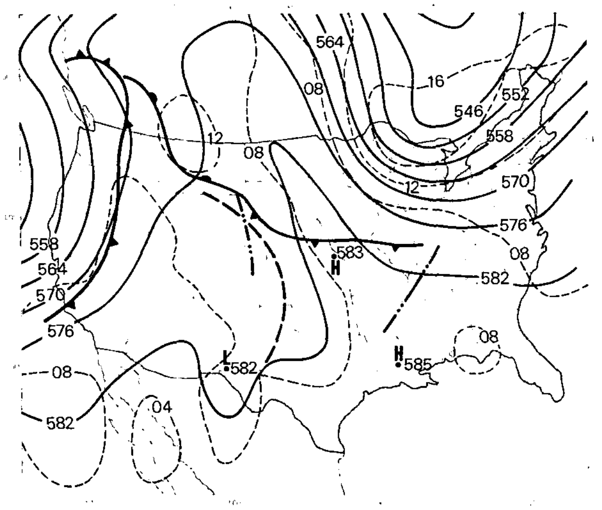

FIG. 15. NMC-LFM vorticity analysis for 0000 GMT 10 June 1972. Refer to legend of Fig. 13 for details.

The storm complexes developed when conditionally unstable and extremely moist air masses pushed upslope into higher terrain. These air masses lay to the north of a polar front, and temperature inversions prevented release of potential instability until the air masses experienced strong orographic lifting. Lower pressures west of the storm areas enhanced the easterly upslope flow.

The storms were triggered just west of a negatively tilted upper level ridge where weak southeasterly steering winds allowed them to remain over the mountains for 2–4 h as new cells generated on the southeast flank and moved into the nearly stationary storm complexes. Weak 500 mb short-wave troughs approaching the storm areas from the south-southwest, eventually moved the storms onto the plains.

a. Common large-scale features

1) A middle and upper tropospheric long-wave trough lies over the western United States with a negatively tilted ridge just east of the threat area.

2) A weak 500 mb short-wave trough rotates northward in the long-wave trough and approaches the threat area.

3) Light southeast to south-southeast (5–20 kt) winds are present in the upper troposphere over the threat area.

4) A slow moving, or stationary, polar front lies just south of the threat area.

5) High moisture content is present through a large depth of the troposphere (surface through 300 mb).

b. Common mesoscale features

1) Afternoon heating west of the threat area and cold advection east of storm area combine to intensify

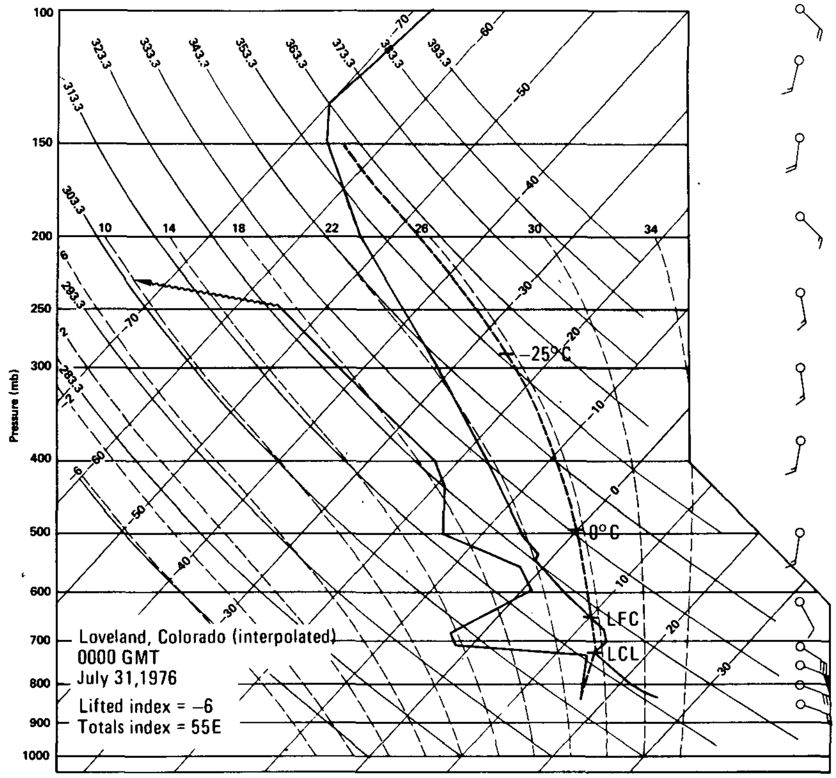

FIG. 16a. Skew $T/\log P$ plot of upper air sounding constructed for Loveland, Colo., at 0000 GMT 1 August 1976. LCL and LFC levels and the moist adiabat are shown for a lifted parcel with mean thermodynamic characteristics of lowest 100 mb layer.

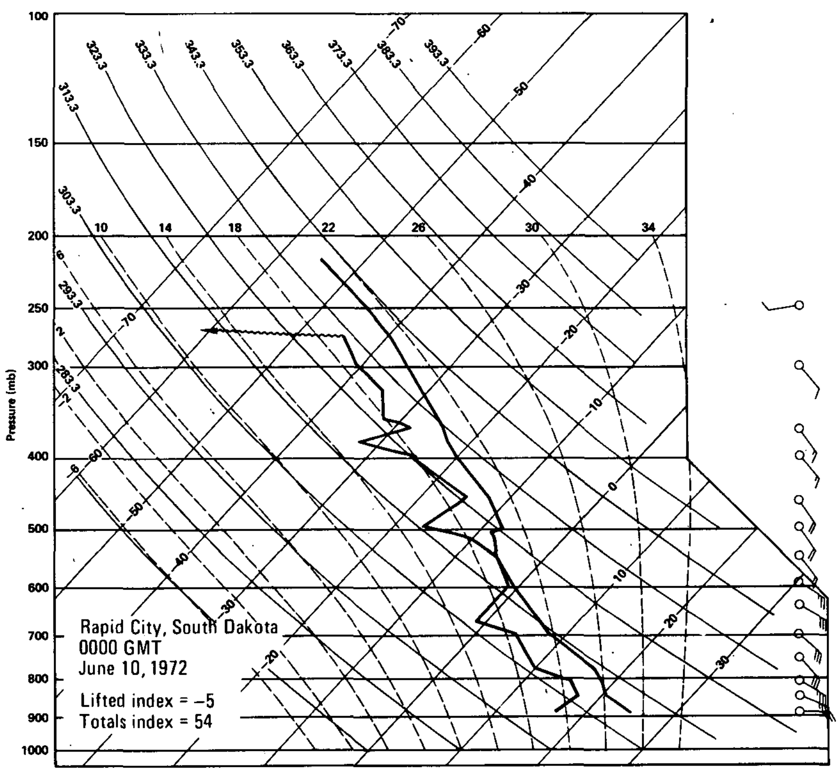

FIG. 16b. Skew $T/\log P$ plot of 0000 GMT 10 June 1972 Rapid City upper air sounding.

TABLE 1. Sounding parameters for the 0000 GMT Rapid City and interpolated Loveland upper air soundings and for a typical severe thunderstorm environment. Severe thunderstorm data are from Maddox (1976).

Location	Time (GMT)	Mean vapor mixing ratio (lowest 100 mb) ($g kg^{-1}$)	Lifted index (lowest 100 mb)	Planetary boundary layer (lowest km) (deg/kt)	Wind velocity (deg/kt)		
					700 mb	500 mb	300 mb
Rapid City	10/0000	14.0	−5	100/40	140/31	150/18	140/08
Loveland (interpolated)	01/0000	14.8	−6	100/50	130/30	190/15	170/15
Typical plains severe storm	—	12 to 14	−4 to −6	200/35	225/40	235/50	245/70

thickness and pressure gradients. Low-level wind flow maximizes about sunset.

2) A narrow band of conditionally unstable (LI = −4 to −7) and unusually moist (vapor mixing ratio of 13–15 g kg^{-1}) air moves southward and westward behind the polar front. This air mass is capped by a temperature inversion.

3) Orographic lift provides the mechanism needed to release the instability, and heavy rains fall over middle elevations of the affected drainages. The moisture content of the low-level air is so great that the lifting needed to trigger storm development is realized east of the highest terrain.

4) Convective cells move slowly north-northwestward and continued cell redevelopment on the southeast flank of the thunderstorm complex results in a quasi-stationary precipitation system.

Most of these important features can be detected and monitored by the forecaster if he uses the NMC facsimile analyses and forecasts in conjunction with radar, satellite and hourly surface data. Accurate delineation of flash flood watch areas requires that the use of mesoscale analysis and interpretation be emphasized in the forecast office (Mogil and Groper, 1976). Once the general threat area has been identified more detailed analysis is required to identify and monitor mesoscale features (such as secondary frontal surges, mesopressure centers, narrow moisture tongues, bands of strong surface winds, etc.) which might act to trigger storms or focus the intense activity in specific locations of the watch area.

Acknowledgments. The authors would like to thank the many persons and organizations who supplied data used in this study. The Department of Atmospheric Science, Colorado State University, provided data for Ft. Collins. Dr. C. Glenn Cobb supplied Greeley data taken at Ross Hall, University of Northern Colorado. James Purdom, of NOAA-NESS Applications Group, supplied copies of GOES imagery. The NHRE and the National Center for Atmospheric Research Field Observing Facility obtained and supplied invaluable sounding, radar and surface data from the NHRE site in northeastern Colorado.

REFERENCES

Caracena, F., R. A. Maddox, L. R. Hoxit and C. F. Chappell, 1977: Big Thompson—A different type of severe thunderstorm. *Preprints Tenth Conf. Severe Local Storms*, Omaha, Amer. Meteor. Soc. 97–103.

Cressman, G. P., 1977: NOAA News Release 77–197, July 20, 1977. Washington, D.C.

Dennis, A. S., R. A. Schlensener, J. H. Hirsch and A. Koscielski, 1973: Meteorology of the Black Hills flood of 1972. Inst. Atmos. Sci. Rep. 73-4, South Dakota School of Mines and Technology, 41 pp.

Fujita, T. T., M. R. Hjelmfelt and S. A. Changnon, 1977: Mesoanalysis of record Chicago rainstorm using radar, satellite, and raingauge data. *Preprints Tenth Conf. Severe Local Storms*, Omaha, Amer. Meteor. Soc., 65–72.

Lott, G. A., 1976: Precipitable water over the United States, Volume 1: Monthly means. NOAA TR NWS 20, 173 pp.

Maddox, R. A., 1976: An evaluation of tornado proximity wind and stability data. *Mon. Wea. Rev.*, **104**, 133–142.

——, 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.

Merritt, L. P., K. E. Wilk and M. L. Weible, 1974: Severe rainstorm at Enid, Oklahoma, October 10, 1973. NOAA TM ERL NSSL-73, 50 pp.

Mogil, H. M., and Groper, H. S., 1976: On the short range prediction of localized excessive convective rainfall. *Preprints Conf. Hydrometeorology*, Ft. Worth, Amer. Meteor. Soc., 9–12.

NOAA, 1976: Big Thompson Canyon flash flood of July 31–August 1, 1976. Natural Disaster Survey Rep. 76-1, Rockville, Md., 41 pp.

NOAA-WR, 1974: Report on the flash flood of September 14, 1974 in El Dorado Canyon, Nevada. Western Region Hdqs., NWS, Salt Lake City, 20 pp.

Randerson, D., 1976: Meteorological analysis for the Las Vegas, Nevada, flood of 3 July 1975. *Mon. Wea. Rev.*, **104**, 719–727.

Schlegel, J., 1976: A comparison of Hurricane Eloise and Hurricane Agnes. *Weatherwise*, **29**, 70–73.

Schroeder, J. A., 1977: Meteorological analysis of an Oahu flood. *Mon. Wea. Rev.*, **105**, 458–468.

Schwarz, F. K., L. A. Hughes, E. M. Hansen, M. S. Petersen and D. B. Kelly, 1975: The Black Hills—Rapid City flood of June 9–10, 1972: A description of the storm and flood. Geol. Surv. Prof. Pap. No. 877, 45 pp.

Sourbeer, R. H., and R. C. Gentry, 1961: Rainstorm in southern Florida, January 21, 1957. *Mon. Wea. Rev.*, **89**, 9–16.

Thompson, H. J., 1972: The Black Hills Flood. *Weatherwise*, **25**, 162–167.

Williams, G., 1976: Application of the National Weather Service flash-flood program in the Western Region. NOAA TM NWS WR-103, 20 pp.

Williams, P., Jr., C. L. Glenn and R. L. Raetz, 1972: Flash flood forecasting and warning program in the Western Region. NOAA TM NWS WR-83, 12 pp.