A Long-Lived Mesoscale Convective Complex. Part I: The Mountain-Generated Component

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(Manuscript received 30 March 1981, in final form 13 June 1983)

ABSTRACT

Using data collected during Colorado State University's South Park Area Cumulus Experiment in 1977, a sequence of multi-scale convective events leading to the formation of a mesoscale convective complex is described. In the first phase, surface-based cool advection in the elevated mountain basin delayed the full transition of the morning boundary layer into a deep mixed layer until well after convective instability was reached over the adjacent ridges. The second phase was earmarked by the formation of convective precipitation echoes at "hot spots" over the high mountain terrain. Two groups of cells then propagated eastward across the mountain basin, forming a line of discrete cells which moved across the foothills toward the High Plains. The cells further intensified at the foothills/High Plains interface and formed a still larger, north–south line of thunderstorms. In the third phase, this north–south line of thunderstorms evolved into an expanding meso-β-scale convective cluster as it continued its eastward propagation over eastern Colorado. The convective intensity of the line was apparently modulated by moisture availability over the plains, with the southern cells being most intense initially. As the northern end of the line encountered greater low-level moisture in western Kansas, the convection rapidly intensified to severe levels and produced in excess of 50 mm of precipitation over a large area. In Part II of this article it is shown that this meso-β-scale system participated in the formation of a meso-α-scale convective complex.

1. Introduction

During the summer of 1977, Colorado State University (CSU) operated a field experiment known as the South Park Area Cumulus Experiment (SPACE). The experiment was centered in a broad, elevated basin (2.7–3.0 km MSL) called South Park, which is nestled just to the west of the Front Range of the Rocky Mountains, northwest of Colorado Springs, Colorado (see Fig. 1). One of the objectives of SPACE was to investigate the evolution of mesoscale structures associated with the formation of mountain thunderstorms and with their subsequent movement eastward onto the Colorado High Plains. The experiment was designed to investigate the organization of the mesoscale and storm-scale systems in detail over South Park and then, using conventional radars, satellite imagery, rawinsondes and widely spaced mesonet stations, observe their subsequent structure over the plains immediately to the east. Using Orlanski's (1975) mesoscale terminology, the experiment was carried out on the mesoscale β and γ scales.

During the course of the experiment, and as a consequence of post-analysis, it has become apparent that many of the convective storms which were observed in the developing stages over South Park, and which propagated eastward, participated in the genesis of mesoscale convective complexes (MCCs) on the meso-α-scale (Maddox, 1980). These mature complexes could be tracked eastward as coherent systems for 2–3 days, sometimes well into the Atlantic Ocean. The period 3–10 August 1977 has been delineated as an "episode", during which MCCs were observed to form daily over eastern Colorado and western Kansas. Extensive heavy precipitation and several instances of flooding were observed in a band from eastern Colorado to New York State as a result of the eastward progression of systems during the episode. On most, but not all, of these days, cumulonimbus convection which formed over the Colorado mountains participated in the genesis of the MCCs.

This two-part paper centers around the multi-scale sequence of events involved with the evolution of the second MCC of this episode, which matured on the evening of 4 August 1977. Part I covers the events from the pre-convective stage early on 4 August to the incipient MCC stage in the early evening, focusing on the convection originating in South Park. First we summarize the design of SPACE in Section 2. Then the synoptic setting for this case is discussed in Section 3. In Section 4, the early evolution of the planetary boundary layer over South Park is described. This is followed in Section 5 by a description of the development of early mountain thunderstorms over the

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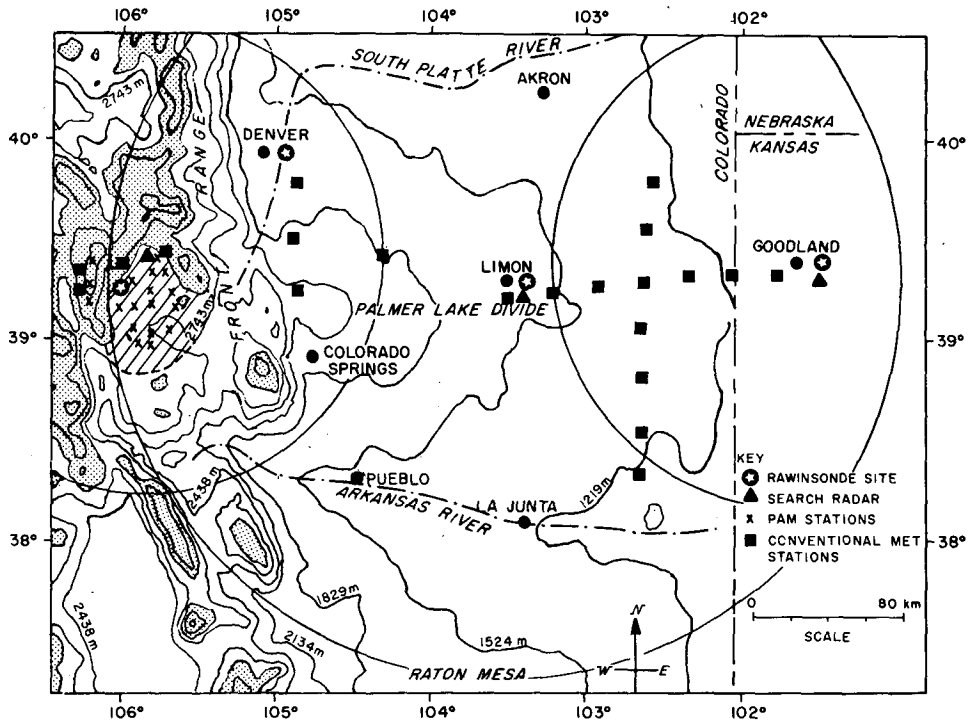

FIG. 1. Map of extended SPACE/HIPLEX experimental area, with averaged terrain contours every 304.8 m (1000 ft) and terrain above 3048 m (10 000 ft) darkly shaded. The hatched region northwest of Colorado Springs represents the elevated basin [between 2743 m (9000 ft) and 3048 m (10 000 ft)] designated as South Park, Colorado. The large circles represent radar effective coverage areas. The CBS-4 radar (not included) is located 7 km southeast of the CP-3 radar.

Park, the mesoscale evolution as they propagated eastward to the Front Range/High Plains interface, and the interaction with other cumulonimbus systems emanating from the foothills. Finally, the further development of intense meso-β-scale thunderstorm systems over the High Plains is described in Section 6. In the second part of this paper, Wetzel *et al.* [(1983) hereafter referred to as Part II] describe the final stages of MCC genesis from these meso-β-scale components, the structure and environment of the mature MCC, and the subsequent modulation of the storm system. A more extensive discussion of the MCC episode is also presented in Part II.

2. South Park Area Cumulus Experiment

CSU's SPACE was a comprehensive summertime meteorological program. The field portion of the program was located in and east of South Park, Colorado (Figs. 1 and 2). To the northeast and southeast of South Park, the eastern slopes of the Front Range drop sharply toward the High Plains interface at about 1.6 km MSL, into the South Platte and Arkansas River valleys, respectively. Directly east of the Park, however, the Palmer Lake Divide, a broad, partially wooded ridge, extends another 100 km onto the High Plains, with elevations of up to 2.1 km MSL. The western edge of South Park, on the slopes of the Mosquito Range, has been recognized as a frequent genesis region for cumulus and cumulonimbus clouds (see Danielson and Cotton, 1977).

During SPACE, observational programs were conducted on several spatial scales. The South Park scale (Fig. 2) is roughly 70 km square. The main SPACE base was located about 10 km south of Fairplay, Colorado, on dry, flat pasture land, about 5 km east of the wooded foothills of the Mosquito Range. The base was the site of the SPACE micrometeorological experiment, which included two Boundary Layer Profiler (BLP) tethered balloons. Rawinsondes were launched from the SPACE base daily at 0600 Mountain Daylight Time (MDT, or GMT − 6 h), 1000 MDT and 1300 MDT. On selected days of interest, rawinsondes were also launched at 1700 and 2100 MDT. Additional instrumentation at the base site, which was not utilized in this study, is described by Danielson and Cotton (1977).

The National Center for Atmospheric Research (NCAR) Portable Automated Mesonet (PAM) was deployed on the South Park scale. Twenty remote weather stations were spaced roughly on a 10 km × 10 km grid, with three (later reduced to two) remote stations located high on the ridge top of the Mosquito Range. Each remote station measured wind speed and direction 4

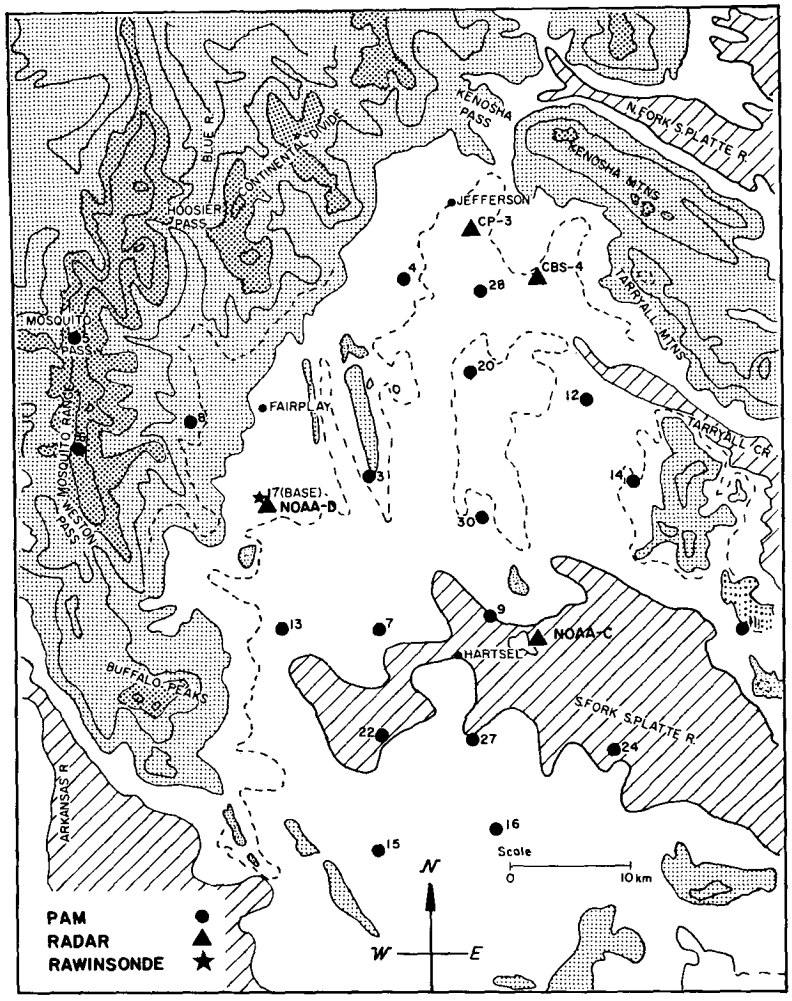

FIG. 2. Map of terrain in South Park, Colorado, with a primary contour interval of 304.8 m. Regions below 2743 m are hatched; regions above 3048 m are lightly shaded and regions above 3658 m (12 000 ft) are heavily shaded. PAM remote stations are indicated with dark circles accompanied by the station number, with a star for the base (and rawinsonde) site. Doppler radars (CP-3, NOAA-D, NOAA-C) and the noncoherent CBS-4 radar are indicated with dark triangles.

m above the ground, wet- and dry-bulb temperatures and pressure 2 m above the ground, and rainfall in 0.25 mm increments with a tipping bucket raingage. The PAM base van was located at the SPACE base, where data were obtained from the remote stations by radio telemetry once per minute. These data were instantly available for display on a computer graphics terminal located in the van.

Triple Doppler radar data were also taken on the South Park scale. The National Oceanic and Atmospheric Administration (NOAA) provided two 3.2 cm Doppler radars, and NCAR provided the 5.5 cm CP-3 radar. NOAA-2 was located at the base, NOAA-1 was 27 km southeast of the base, and CP-3 was 30 km northeast. Reflectivity data from these radars were utilized in this study. After 1 August 1977, the CSU 10 cm FPS-18 radar (CBS-4) was available to perform full volume scans. This radar was located on higher ground ~7 km southeast of CP-3, where it had a much better view toward the east.

During the period 1–13 August, the U.S. Bureau of Reclamation (BuRec) provided two aircraft, the University of Wyoming Queenair and the Meteorological Research Inc. Navajo. The aircraft were used in this study to determine cross sections between South Park, Colorado and Goodland, Kansas.

In conjunction with the BuRec High Plains Experiment (HIPLEX), the SPACE program also gathered data over a region approximately 500 km (east to west) by 200 km (north to south) extending from west of South Park to east of Goodland, Kansas (Fig. 1). Three rawinsondes were launched daily by CSU from Limon, Colorado and two or three were launched by HIPLEX at Goodland, Kansas. These were supplemented by

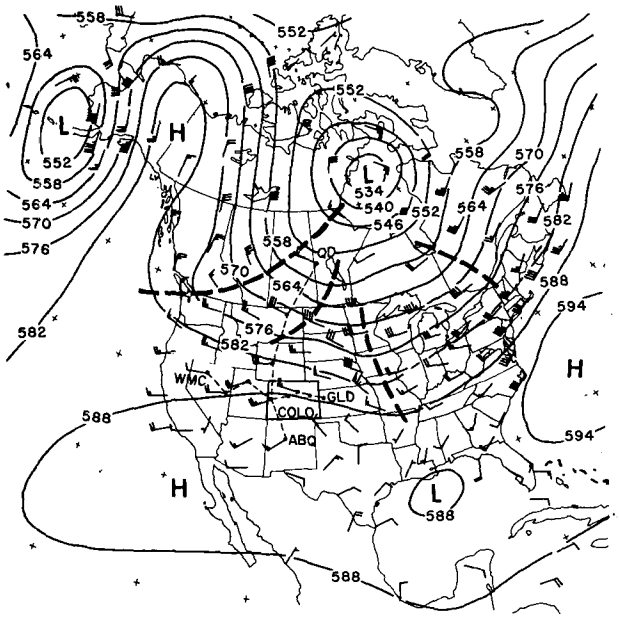

FIG. 3. Continental-scale 50 kPa height analysis for 0600 MDT 4 August 1977. Heavy dashed lines denote short-wave troughs. Height contours are labeled in decameters. Wind pennants, full barbs and half barbs denote 25, 5 and 2.5 m s^{-1}, respectively. The dotted lines WMC-GLD and QD-ABQ show the cross section locations used in Figs. 6 and 7, respectively.

regular National Weather Service (NWS) soundings taken at Denver and other NWS sites. Seventeen recording surface stations were maintained between the Front Range and Goodland. In addition to the CSU FPS-18 radar previously mentioned, data were available from the NWS 10 cm WSR-57 radar at Limon (PPI photos and traces only) and the HIPLEX 5 cm radar at Goodland. These three radars generally provided continuous coverage of eastward moving storms from the central Rockies to western Kansas.

Visible (VIS) and infrared (IR) satellite data applicable to this larger scale were available, with several days' data digitized and stored on magnetic tape. On 4 August 1977, "rapid scan" satellite imagery were available at 3 min intervals, and supplementary rawinsonde data were taken at 1200 MDT at five NWS rawinsonde sites, including Denver and Grand Junction, Colorado.

3. Synoptic situation

At 0600 MDT 4 August 1977, the large-scale pattern at 50 kPa over North America was dominated by a broad, closed cyclonic circulation centered over Hudson Bay (Fig. 3). This long-wave pattern had evolved over the previous several days from an initially higher-amplitude pattern, which had featured a deep trough over the east-central United States and a northwestward extension of the subtropical ridge from west Texas and northern Mexico into northern California. This flattening long-wave trend continued for one more day, so that the initial strong meridional flow over most of the United States evolved into a more general zonal flow across the northern United States that persisted throughout the episode.

Embedded within this flow at 0600 MDT 4 August (Fig. 3) were a series of weak short waves, as indicated

FIG. 4. Enhanced IR image of the United States at 0300 MDT 4 August 1977, from the GOES satellite at 70°W longitude. The stepped gray shades of medium gray, light gray, dark gray and black are thresholds for areas with apparent blackbody temperatures colder than −32, −42, −53 and −59°C, respectively. Temperatures progressively lower than −63°C appear as a gradual black-to-white range. The cloudiness over Utah indicates the mid-level moisture source for convective development on 4 August over the Colorado mountains. The intense meso-α-scale convective complex (MCC) centered over eastern Kansas originated in the eastern Rockies and western plains the previous evening.

by the heavy dashed lines. One of these, located over the upper Mississippi Valley, was associated with the first MCC of the episode (Fig. 4) which developed in eastern Colorado and Wyoming on the evening of 3 August. As seen in the 3 h mesoscale sea-level pressure analyses for the period 1800 MDT 3 August to 1800 MDT 4 August (Fig. 5), this first MCC produced a mesoscale high-pressure system as it developed and propagated across Nebraska and Kansas, leaving relatively cool, moist air in its wake. The southern boundary of this meso-high persisted as a pressure, temperature and moisture discontinuity across southern Kansas, and it played an important role in the development of the second MCC on the evening of 4 August, as discussed in Part II.

Farther to the northwest on the morning of 4 August (Fig. 3), two short waves, one of which was very weak, were entering the northern Rocky Mountain states. Both of these waves were linked to southward surges of cool polar air at the surface. The first of the cold

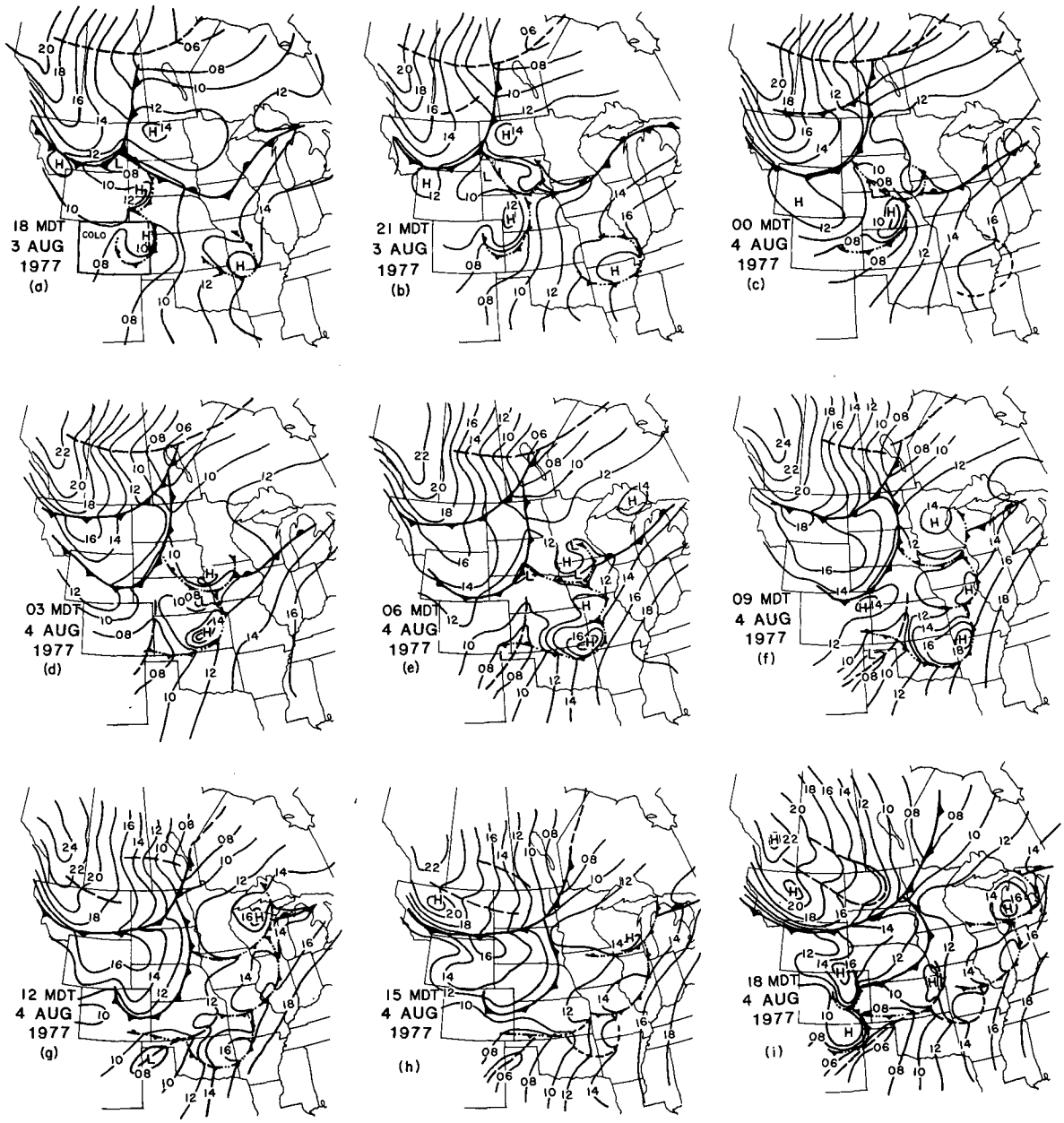

FIG. 5. Mesoscale analyses of surface pressure reduced to sea level (contours labeled in 10^{-1} kPa, with prefix of 10 omitted) and surface discontinuities (fronts, troughs and mesohigh boundaries): (a)–(i) cover the 24 h period 1800 MDT 3 August to 1800 MDT 4 August 1977, at 3 h intervals.

fronts, initially the stronger of the two, had moved southward from Montana through the night, pushing into Colorado about mid-morning (Figs. 5a–f). This surge of air was too shallow to climb the Front Range and directly affect cumulus formation over South Park. However, its northeasterly flow enhanced low-level moisture convergence over northeastern Colorado in the afternoon (Figs. 5g–h) and helped intensify the cumulonimbus systems emanating from the Front Range onto the High Plains (Fig. 5i), as discussed in Section 6. By 1200 MDT (Fig. 5g), as this first front was weakening and stalling across eastern Colorado, the second front was approaching Wyoming. The second surge of cool air, supported by the stronger shortwave trough at 50 kPa, became the dominant synoptic feature by the afternoon of 4 August and continued to push southeastward (Fig. 5h–i). The effect of this front on the later evolution of the convective system is discussed in Part II.

Over western Colorado and much of Utah early on 4 August, an area of mid-level convective cloudiness seen on the IR satellite image (Fig. 4) suggests a moist, rather unstable airmass in a region of weak anticyclonic flow at 50 kPa. Dew points in this region had increased over the last several days as the long-wave evolution, described above, was accompanied by a gradual backing of mid- to upper-level winds over the west-central United States from northwesterlies to general westerlies. The resulting cloudiness corresponds to a deep layer of mid-level moisture centered over Salt Lake City, evident in an east–west cross section at 0600 MDT 4 August (Fig. 6, indicated by dotted line in Fig. 3). Note also in Fig. 6 the mountain-induced wave features apparent in both the potential temperature and relative humidity fields, and the general lack of any concentration of isentropes in the troposphere which would suggest the presence of a front or other synoptic feature.

In a concurrent north–south cross section through western Colorado (Fig. 7, along N–S dotted line in Fig. 3), the isotach field shows the moist airmass to be on the anticyclonic-shear side of a weak double jet stream over Wyoming. This jet feature has many characteristics which identify it as a subtropical jet (Palmén and Newton, 1969). Baroclinicity associated with this jet is restricted to a weak "jet front" extending down only to 40 kPa. The polar-front jet at this time was located near the United States/Canada border in association with the two surface cold fronts.

Regional objective analyses of upper-air data confirm that this basically subtropical synoptic environment over the southern Rocky Mountain plateau on 4 August was relatively weak, though favorable for the de-

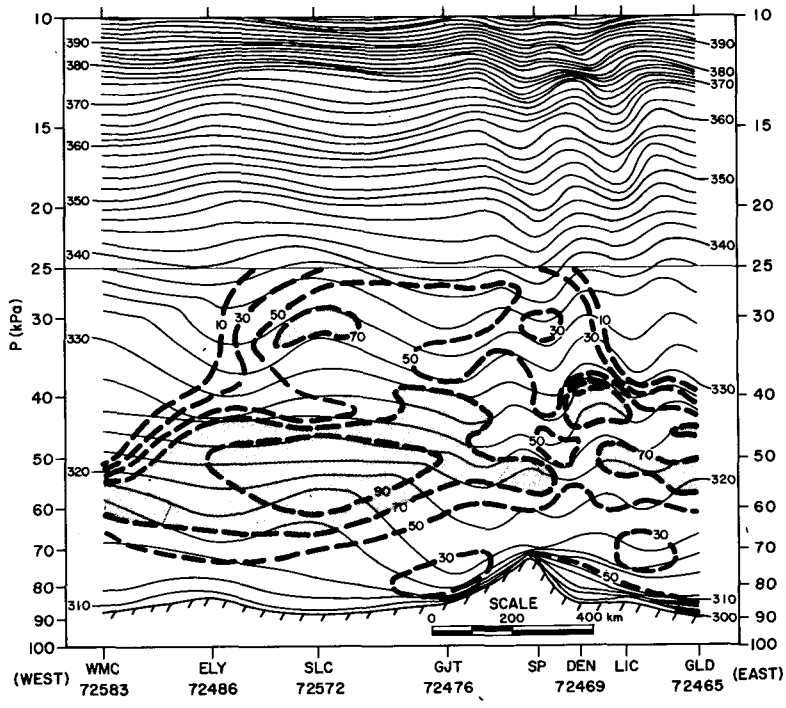

FIG. 6. East–west cross section near 40°N (along dotted line in Fig. 3) for 0600 MDT 4 August 1977. WMO stations (identified by international number in figure) include Winnemucca (WMC) and Ely (ELY), NV; Salt Lake City (SLC), UT; Grand Junction (GJT) and Denver (DEN), CO; and Goodland (GLD), KA. Non-WMO stations are the base site in South Park (SP) and Limon (LIC), CO (see Fig. 1 for locations). Shown are isentropes (*K*, solid lines) and relative humidity (%, dashed). Areas of relative humidity greater than 70% are stippled.

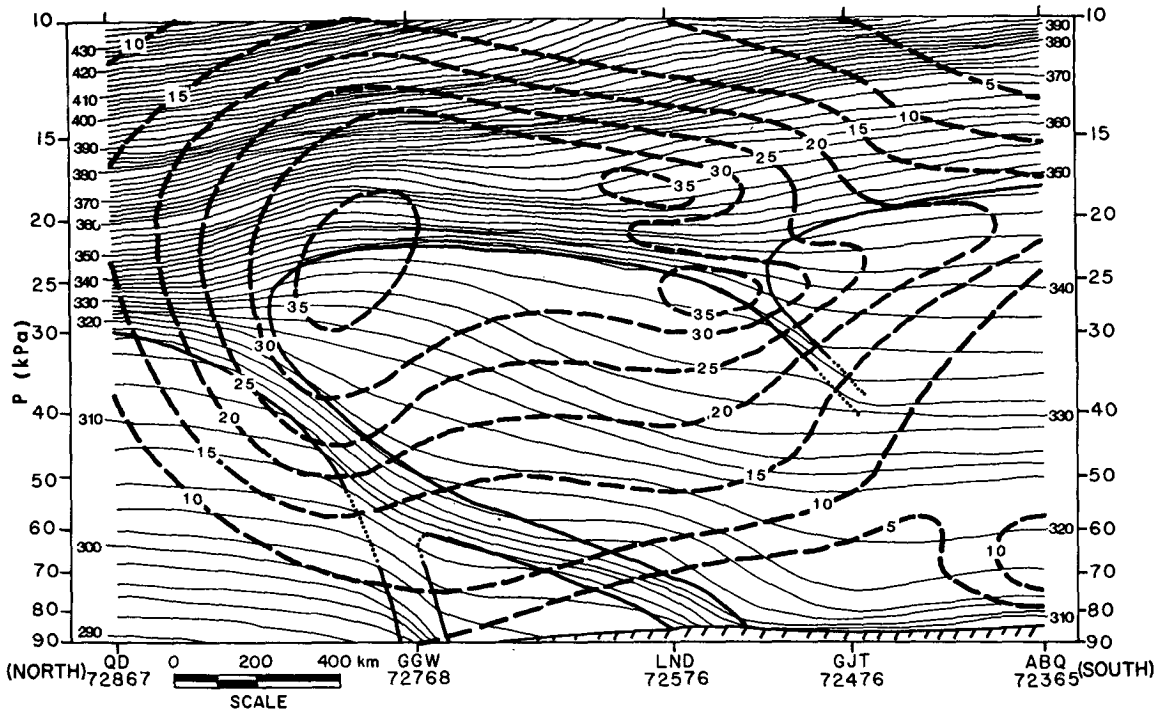

FIG. 7. North–south cross section near 107°W for 0600 MDT 4 August 1977. WMO stations (identified by international number in figure) include the Pas (QD); Manitoba; Glasgow (GGW), MT; Lander (LAN), WY; Grand Junction (GJT), CO and Albuquerque (ABQ), NM. Shown are isentropes (K, solid lines) and isotachs (m s^{-1}, dashed).

velopment of mountain-generated convection and its subsequent growth. (The Appendix contains a description of the objective analysis technique.) Figs. 8a–b show the 50 kPa fields of height, absolute vorticity, winds and mixing ratio (q) in excess of 3 g kg^{-1} at 0600 and 1800 MDT 4 August. Three axes of maximum vorticity (denoted by the bold dashed lines) at 0600 MDT (Fig. 8a) correspond to the three short waves in Fig. 3, described earlier. The vorticity axis in Montana, associated with the first cold surge advancing southward through the plains, has a weak extension into northeast Nevada. A separate vorticity axis extends from southern California into Arizona. Downstream from these short waves, which are industinguishable in the height field, is an axis of minimum vorticity extending from central Colorado into southwest Wyoming, associated with a weak mid- to upper-tropospheric ridge. Weak positive vorticity advection (PVA) between these maximum and minimum vorticity axes may have enhanced the orographic lifting over the western slope of the Rocky Mountain plateau (see topographic contours in Fig. 9b), leading to the moist (shaded) region over Utah and northern Arizona (seen also in the cross section in Fig. 6).

By 1800 MDT (Fig. 8b), the convection originating in the mountains had propagated onto the High Plains of eastern Colorado and was continuing its upscale growth into a mesoscale convective system (see Fig. 25 for an IR perspective of this development). The southern extension of the vorticity axis that was associated with the North Dakota short wave had lost its identity by this time. However, the southern vorticity axis, embedded within the region of relative anticyclonic flow over the southwestern United States, had propagated to northeast Arizona, maintaining weak PVA downstream to the axis of minimum vorticity, now over eastern Colorado. The leading edge of the mid-level moist region had advected within the weak PVA field to eastern Colorado by now, coincident with the mesoscale convective system. The initial convection that developed over South Park earlier in the day occurred just after the passage of this mid-level moisture front across central Colorado.

The height field at 70 kPa at 1800 MDT was also devoid of any strong wave feature in the vicinity of Colorado (Fig. 9a). However, abundant moisture ($q \geqslant 6$ g kg^{-1}) was being advected across the Continental Divide by southwesterly winds at 70 kPa, as well as being lifted to the 70 kPa level along the High Plains by lower-tropospheric upslope flow (represented by the 1800 MDT wind field at 85 kPa in Fig. 9b). Also in Fig. 9a is the 85–50 kPa thickness field, with the maximum thicknesses centered over New Mexico and Arizona. This thickness pattern closely resembles both the 85 and 70 kPa temperature fields over the southwestern United States (not shown) and had increased by ~30 m over this region since 0600 MDT, due to diurnal heating of the low- to mid-troposphere over

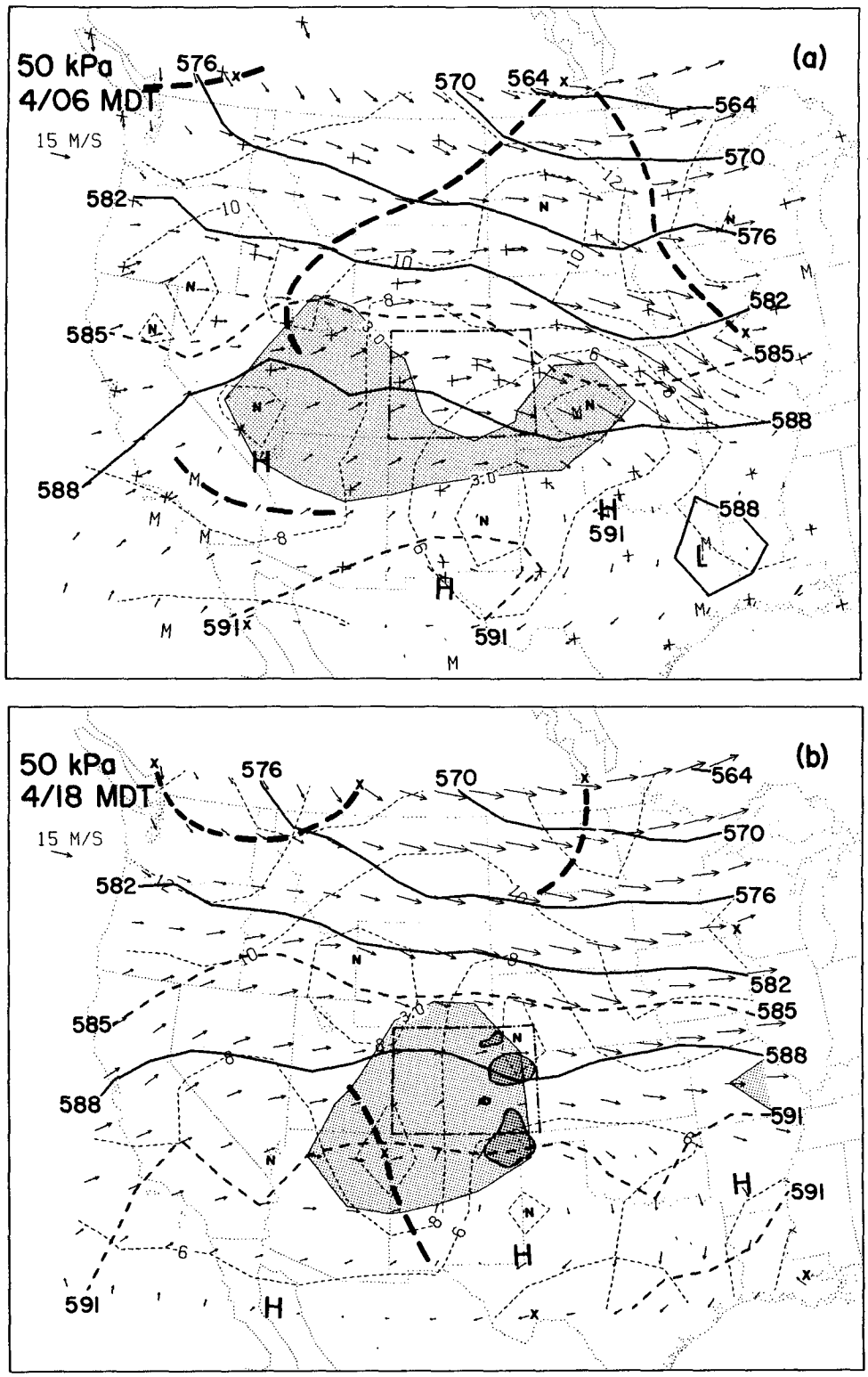

FIG. 8. Regional-scale objective analyses (see Appendix for details) for 50 kPa on 4 August at (a) 0600 MDT and (b) 1800 MDT. Analyzed fields include height (heavy contours, dm), absolute vorticity (thin dashed contours, 10^{-5} s^{-1}), mixing ratio in excess of 3 g kg^{-1} (lightly shaded regions) and winds (tails at grid points). Routine and supplementary rawinsonde winds are also shown (+ at station sites; M denotes missing wind). All winds are proportional to the 15 m s^{-1} key vector in the upper left. Bold dashed lines denote axes of maximum vorticity, and Xs and Ns denote local vorticity maxima and minima, respectively. The dark shading in (b) denotes IR cloud-top temperatures colder than −53°C.

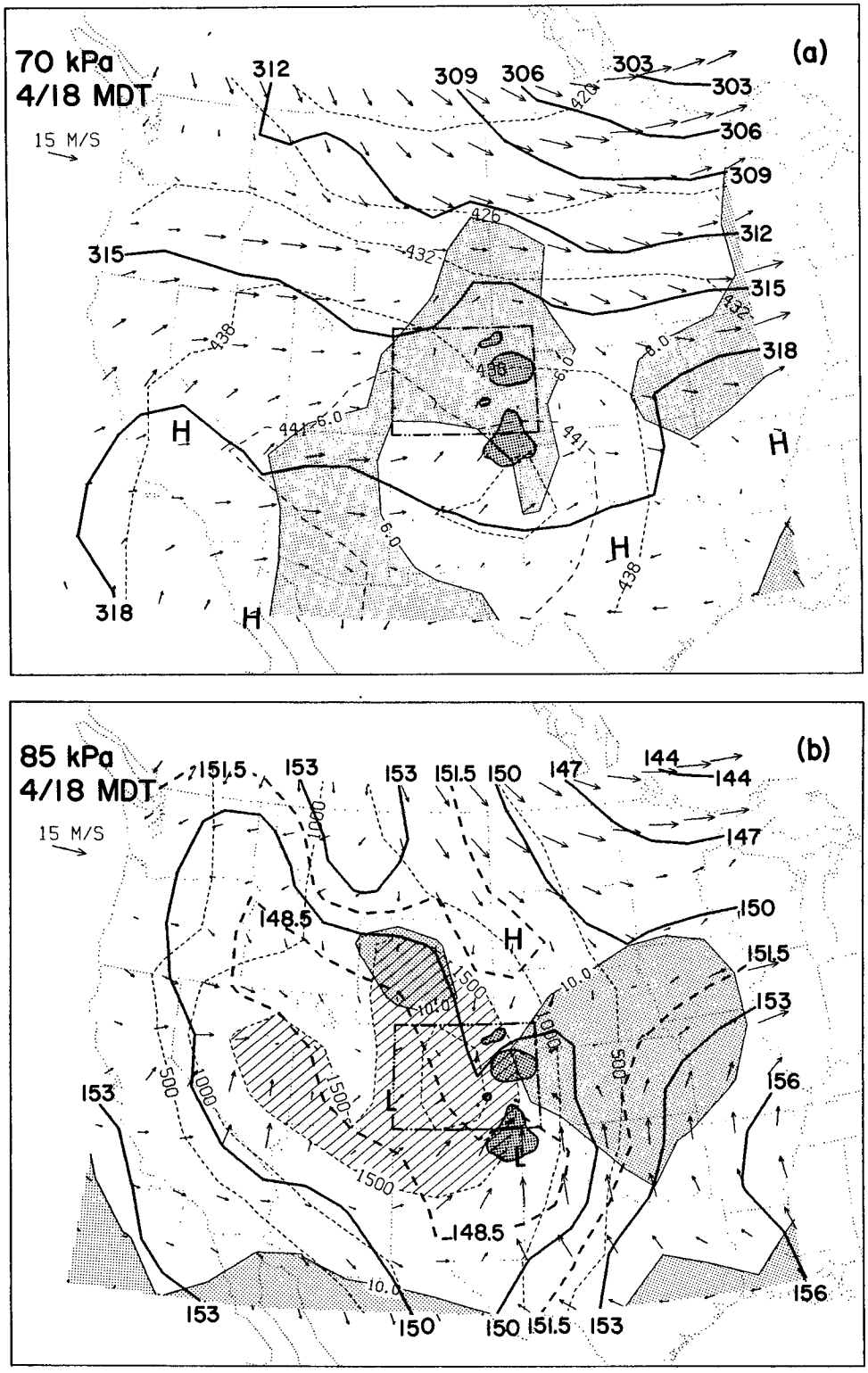

FIG. 9. Regional-scale objective analyses at 1800 MDT 4 August for (a) 70 kPa height (heavy contours, dam), winds (proportional to the 15 m s^{-1} key vector in upper left), $q \geqslant 6$ g kg^{-1} (lightly shaded region) and 85–50 kPa thickness (thin dashed contours, dm) and for (b) 85 kPa height, winds and $q \geqslant 10$ g kg^{-1} [conventions as in (a)] and gridded terrain contours (thin dashed lines, *m*). The hatched region in (b) above 1500 m elevation denotes terrain higher than the 85 kPa level, where surface parameters and reduced 85 kPa heights were used in the analyses. The darkly shaded areas in eastern Colorado are as in Fig. 8b.

the Rocky Mountain plateau. (Thickness over the northern plateau had remained about the same because of the negating effect of cool advection.) Thus, warm advection by southwesterly to westerly winds in the low- to mid-troposphere helped destabilize the moist airmass crossing the plateau over Colorado.

At 85 kPa at 1800 MDT, a trough extended from northeast New Mexico northeastward across the plains into Minnesota (Fig. 9b). On the Colorado High Plains north of this trough, moist, northeasterly upslope flow associated with the now stalled cool surge was feeding moisture into the developing convective system. South of the trough, warm, moist, southeasterly upslope flow fed the system. This low-level pressure pattern enhanced the diurnal upslope flow that develops with great regularity on the High Plains during summer afternoons (Johnson and Toth, 1982). With due regard to the manner in which the 85 kPa winds were analyzed in this high-elevation region, the computed 85 kPa velocity divergence field (not shown) suggests pronounced convergence over the High Plains of Colorado and New Mexico, with the largest magnitudes in southeast Colorado. The increase in 85 kPa convergence over this region from 12 h earlier at 0600 MDT is consistent with the mean summertime morning-to-evening divergence tendencies at 1220 m AGL found by Bleeker and Andre (1951), which they also attributed to large-scale, diurnal orographic circulations.

While warm advection was present over most of Colorado at 1800 MDT (as suggested by Fig. 9a), the warm advection patterns at 85 and 70 kPa (not shown) were only about half the magnitude and much less extensive than those found by Maddox and Doswell (1982) to be associated with the beginning stages of a pair of MCCs over the more level terrain of the Northern Plains. In fact, northeastern Colorado was under the influence of cool advection, associated with the stalled cool surge from the north. It is hypothesized that in this case, the diurnal, orographic upslope flow, enhanced by the weak cool surge and the low-level trough in the region, provided an alternate lifting mechanism by which the mountain-generated convection could develop upscale into an MCC on the High Plains.

In summary, the environmental airmass within which South Park convection developed on 4 August was apparently of subtropical nature, being on the anticyclonic side of a subtropical jet. Vertical motion associated with large-scale orographic lifting, thickness advection and weak PVA helped destabilize this moist westerly flow. The dominant feature which influenced the development and early growth of the convection over the High Plains of eastern Colorado was low-level, convergent, diurnal upslope flow, enhanced by a rather shallow mass of cooler air which entered Colorado from the north on the morning of 4 August. Later development of the convection into an MCC was influenced by an outflow boundary left by the previous day's MCC and by a second, more dominant surge of cool air (discussed in Part II).

4. Morning evolution of the planetary boundary layer in South Park

In the previous section, significant features of the synoptic, pre-convective environment that affected South Park on 4 August were discussed. In this section, surface mesonet (PAM), rawinsonde and tethered-balloon data are used to describe the finer-scale structure of the atmosphere over South Park, and to depict its modifications which led to the development of the first clouds over the Mosquito Range on the west side of the Park.

At 0600 MDT the South Park sounding (Fig. 10) showed a very thin nocturnal radiation inversion, topped by a near-neutral layer to 53 kPa. Westerly winds increased upward to 7–10 m s^{-1} within this layer with very little directional shear. Above 53 kPa, the mid-troposphere was stratified into several thin mixed layers, separated by stable layers. The convective condensation level (CCL) for a mixed surface layer 10 kPa deep was 52 kPa. A cloud with its base at the CCL would be capped by the stable layer at 48 kPa, but if this stability were eliminated the cloud parcel could

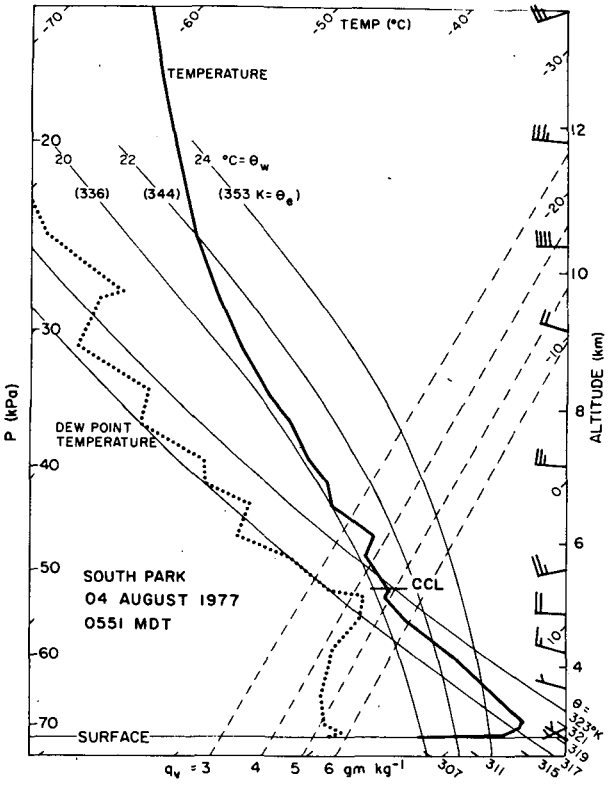

FIG. 10. South Park sounding at 0551 MDT 4 August 1977, plotted on skew-T log-P diagram. A full wind barb represents 5 m s^{-1}. The convective condensation level for an approximate 10 kPa mixed surface layer is marked.

then rise undiluted to at least 31 kPa (9 km MSL) before losing buoyancy.

Surface winds, potential temperature (θ), water vapor mixing ratio (q_v) and equivalent potential temperature (θ_e) for this time (Fig. 11) show that very light winds were prevalent within the Park, and they primarily flowed downhill below the nocturnal inversion. Most wind directions reflect a drainage flow toward the low-lying valleys in the center of South Park. Water vapor mixing ratios were almost uniform throughout South Park, averaging ~5.3 g kg^{-1}.

Soundings from a Boundary Layer Profiler (BLP) tethered balloon system were taken during the early morning at a site 2.4 km west of the CSU base over a flat pasture ("remote" soundings). The system was transferred from the remote site to the CSU base at about 0800 MDT. Case studies of boundary-layer evolution using BLP soundings taken at the CSU base have already been described by Banta and Cotton (1981). These indicate that the morning downslope winds below the radiation inversion switched to upslope 1–2 h after sunrise. Upslope winds formed in a thin unstable boundary layer which was potentially cooler than the neutral layer above. On the dry, convectively suppressed days studied by Banta and Cotton, rapid turbulent mixing occurred as the convective boundary layer grew into the neutral layer, due in part to the strong westerly winds which prevailed in the neutral layer. These dry westerlies were then entrained to the surface, creating a sudden surface wind shift accompanied by rapid decrease in surface moisture.

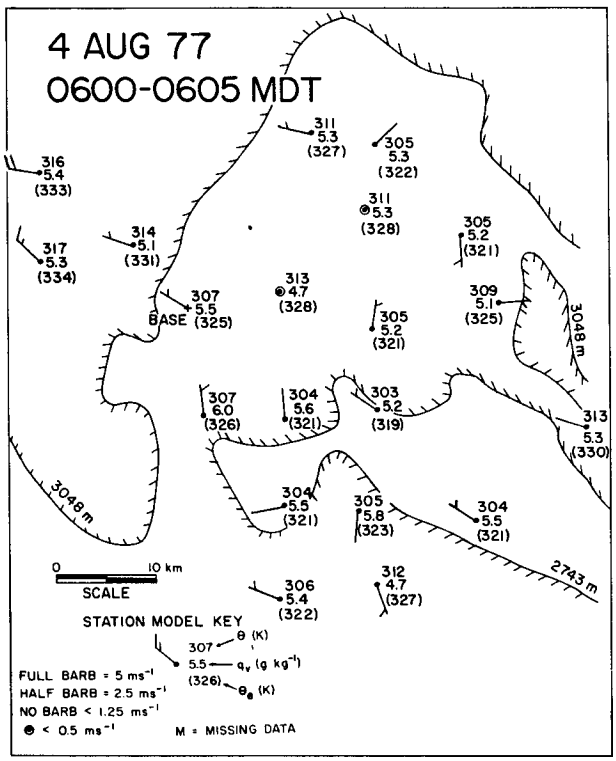

FIG. 11. PAM surface data from South Park for 0600–0605 MDT 4 August 1977. Five-minute averaged potential temperature, water vapor mixing ratio, equivalent potential temperature and winds are plotted at each station (see key for plotting conventions). Smoothed terrain contours of 3048 m and 2743 m delineate higher ground toward the ridges to the west through north and northeast, and lower ground of the South Platte River valley (draining out the southeast of South Park), respectively (refer to Fig. 2 for detailed topography).

On 4 August, however, a somewhat different sequence of events occurred. The soundings from the remote site (Figs. 12a–c) show the evolution of the boundary layer just after sunrise. The initial strong nocturnal inversion at 0620 MDT (Fig. 12a) was weakened and partially destroyed as a mixed layer 40 m deep had formed within the inversion by about 0700 MDT (Fig. 12b). Winds from both early soundings were basically downslope westerlies throughout. By 0730 MDT (Fig. 12c), the mixed layer had deepened to ~100 m, with very light winds compared to the continued strong westerlies above 100 m. Winds near the surface had begun to turn easterly. The lapse rate was somewhat stable near the surface, indicating the possibility of advection of cool moist valley air by the incipient upslope winds. By 0830 MDT, mixing ratios had increased from pre-sunrise values of 5.5 gm kg^{-1} to over 6.5 gm kg^{-1} at some valley PAM stations. A base site BLP flight beginning at 0836 MDT (Fig. 12d) confirmed this hypothesis. Winds with a stronger upslope component in the lowest 50 m of the sounding brought increased moisture and somewhat cooler air over the CSU base.

The pattern of boundary-layer evolution at the CSU base can be further examined using a time sequence of surface potential and dew-point temperatures (Fig. 13). After sunrise, θ rose rapidly until about 0820 MDT, when cool advection began, along with wide fluctuations in dew point. After 0900 MDT, θ began to increase again, but it did not reach 321 K, the potential temperature of the elevated neutral layer over South Park (Fig. 10), until after 1100 MDT. Thus, development of deep convection capable of reaching saturation did not occur over the base and lower-laying areas until after 1100 MDT.

A pattern of light but coherent valley winds prevailed in central South Park at 1000 MDT (Fig. 14a). Several stations had mixing ratios of over 6.5 g kg^{-1}. The location of these stations coincided well with the valley of the South Platte River. This pattern of light, moist valley winds persisted through 1100 MDT (Fig. 14b). The higher western stations at 1000 MDT had potential temperatures of up to 321 K, indicating that moist convection was possible at those locations. In fact, the first small cumulus clouds were observed over the Mosquito Range at about 1000 MDT.

The 1030 MDT South Park sounding (Fig. 15) indicated substantial moistening of all levels since the early morning sounding (Fig. 10). Above the CCL, the higher dew points resulted from westerly moisture ad-

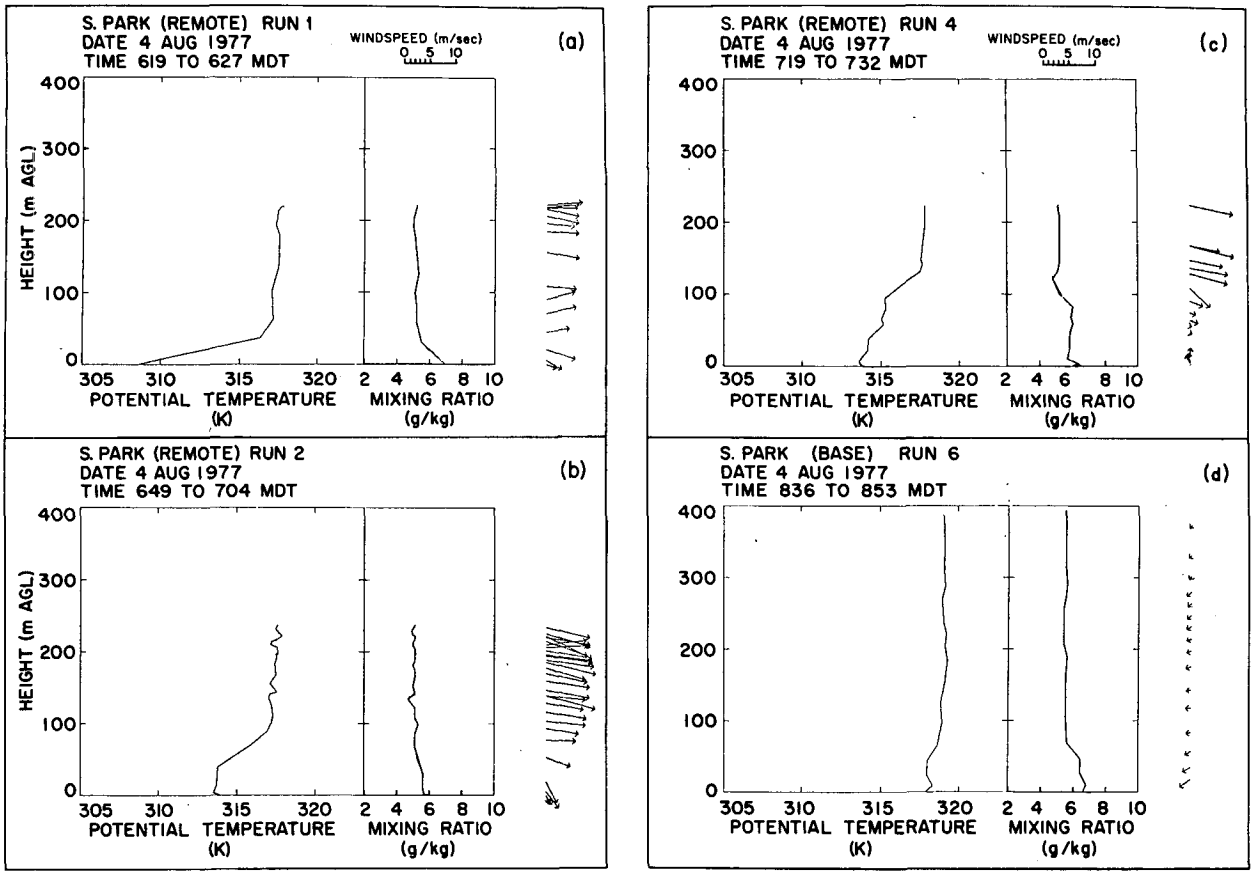

FIG. 12. Boundary Layer Profiler (BLP) tethered balloon soundings. Potential temperature, water vapor mixing ratio and winds, plotted against height (m AGL). Remote site soundings began at (a) 0619 MDT, (b) 0649 MDT and (c) 0719 MDT 4 August 1977; base site sounding (d) began at 0836 MDT.

vection (see Figs. 6 and 8a), while the moistening of the deep neutral layer below the CCL was probably due to mixing of moisture provided by a convergent surface-based flow (southeasterly upslope over central South Park, westerly at ridge-top level, as shown in Fig. 14). A layer of conditionally unstable air extended to 43 kPa. This was the layer in which the first cumulus clouds formed. The stable layer at 48 kPa, which had been present on the earlier sounding, was almost entirely eliminated. A low-level parcel with a mixing ratio of 6 g kg^{-1}, if lifted on this sounding, would reach saturation at about 54 kPa, and could rise to a potential cloud top of 27 kPa (10 km AGL) before losing buoyancy.

A BLP sounding taken at 1100 MDT (not shown) showed a well-mixed planetary boundary layer (PBL) to at least 350 m, with θ = 320 K and q_v > 6 gm kg^{-1} in upslope winds. The prolonged low-level stability due to morning valley winds over lower areas of South Park served to suppress deep PBL growth and to inhibit cumulus cloud formation. However, surface potential temperatures of up to 324 K were observed over the high ridge of the Mosquito Range (Fig. 14b) during the same time period, indicating that deeper convection had already developed. The time evolution of the convection in this "mountain boundary layer" is revealed in Fig. 16, a time plot of θ, dew point (T_d) and wind velocity at station 6, which was located west–northwest of the base (see Fig. 2) on Horseshoe Peak at an ele-

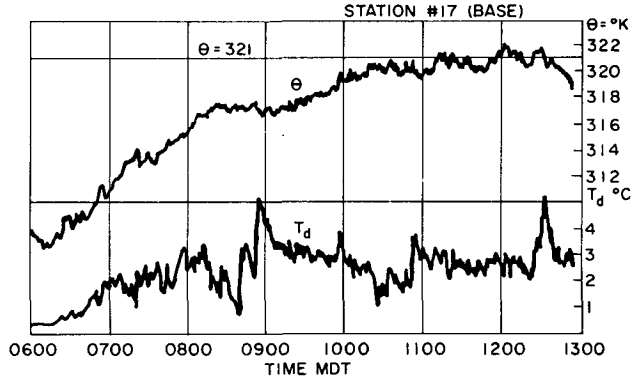

FIG. 13. Plot of potential temperature and dew point versus time, at the base, 0600–1300 MDT 4 August 1977.

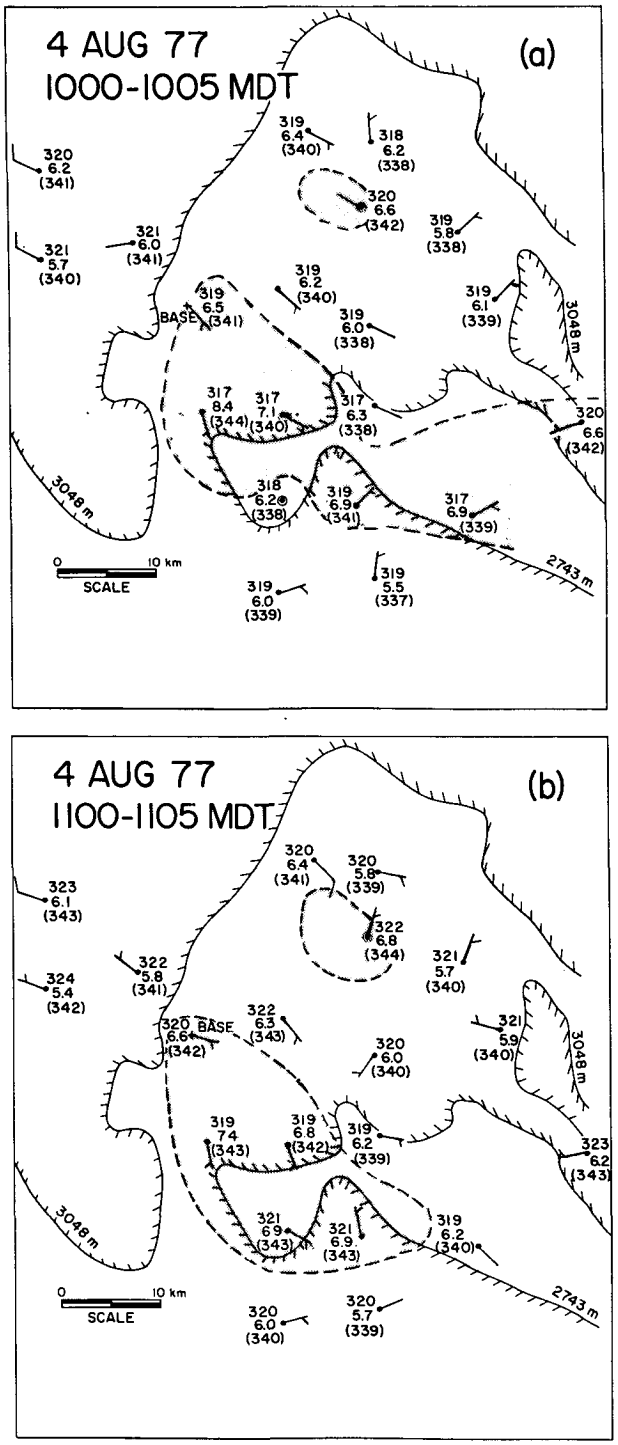

FIG. 14. As in Fig. 11 except for (a) 1000–1005 MDT and (b) 1100–1105 MDT 4 August 1977. Shaded region denotes area with water vapor mixing ratio at or exceeding 6.5 g kg^{-1}.

vation of over 4.2 km MSL (61.5 kPa). Sharp jumps in θ were evident shortly after 0900 MDT and just before 1000 MDT, both accompanied by a drop in wind speed. Moisture remained relatively constant at 5.5 gm kg^{-1} (T_d near −2°C). The 1030 MDT South Park sounding (Fig. 15) shows that a parcel with θ = 323 K and q_v = 5.5 g kg^{-1} might barely reach saturation and form a cloud with its base at 53 kPa. It is hypothesized that the mountaintop jump in θ represents the consolidation and lifting of a large bubble of air which had been heated by insolation on the protected east-facing slopes of the mountains. The sudden decrease in θ at 1000 MDT, with a sudden rise in wind speed, may represent an incursion of cooler, free-environmental air in the wake of the rising bubble. After 1000 MDT, the high values of θ and sufficient moisture in Fig. 16 suggest that Horseshoe Mountain became an almost continuous source of cloud bubbles.

Conditions favorable for cumulus cloud formation or propagation over the South Park basin did not occur until after 1200 MDT, when a potential temperature of 321 K was present at most of the surface stations. A BLP sounding taken from the CSU base at about 1220 MDT (not shown), the time of the first radar echoes in South Park, showed well-mixed profiles of θ > 321 K and q_v > 6 g kg^{-1} in southeasterly upslope winds.

To summarize the boundary layer evolution to the point of the initiation of deep cumulus convection, drainage winds served to pool stable air in the lower

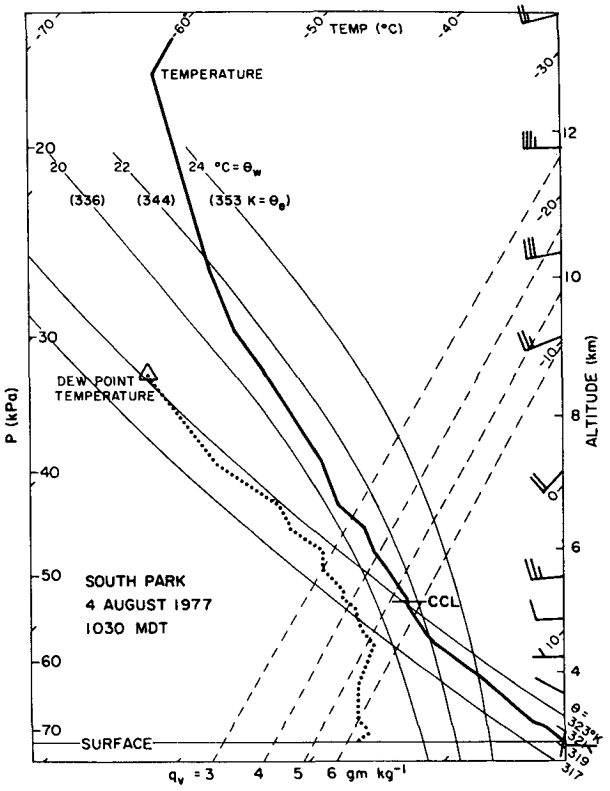

FIG. 15. South Park sounding of 1030 MDT 4 August 1977 (as in Fig. 10).

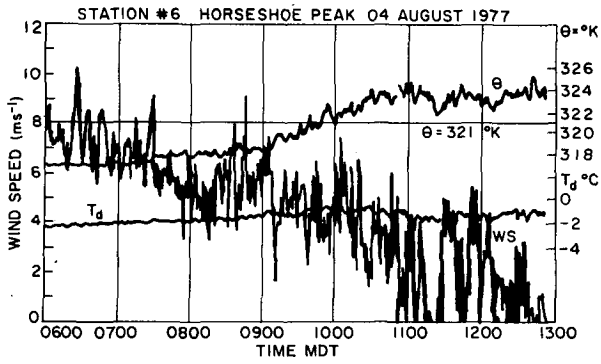

FIG. 16. Temperature, dew point and wind speed (1 min values) plotted versus time, at PAM station No. 6 (Horseshoe Peak), for 0600–1300 MDT 4 August 1977.

areas of the Park overnight. After sunrise, light slope winds within the growing boundary layer tended to redistribute static stability more uniformly over the relatively flat Park while local surface heating rapidly created a well-mixed, unstable boundary layer over the higher mountains. Thus, cumulus growth was enhanced over the mountains and suppressed over South Park. Cumulus clouds formed over Horseshoe Peak by 1000 MDT, while clouds were inhibited over the Park until a deep unstable boundary layer was achieved after 1200 MDT.

Observed PBL wind speeds were usually 3 m s^{-1} or less; these winds were established by about 0800 MDT. Thus, the trajectory of a typical upslope parcel from 0800 until 1200 MDT would be less than 50 km long, insufficient to advect moisture from outside of South Park to the area of cloud genesis west of the CSU base. As previously noted, the easterly flow behind the stalled front across the Colorado plains (Fig. 5) was too shallow to advect moisture into South Park. Therefore, the observed increases in surface moisture before the onset of deep mixing must have come primarily from local evaporation or advection from neighboring river valley floors. Analyses of several other cases indicate that larger-scale advection of moisture from the plains westward into South Park by slope winds is most likely to occur in the late afternoon. Thus, low-level moisture with its origins in the western plains (loosely termed "Gulf of Mexico moisture") and which helps fuel early afternoon thunderstorms over South Park, is likely to have arrived the day before. On 4 August 1977, sufficient low-level moisture was already present in South Park, which, when coupled with advection of moisture above mountaintop level from the west ("Pacific moisture"), provided conditions ripe for the development of widespread deep, moist convection.

5. Midday development and propagation of the mountain thunderstorms

In the previous section, it was shown how the evolution of the PBL over South Park on 4 August was influenced by light slope winds caused by surface thermal effects on mountain slopes. These effects resulted in the formation of the first cumulus clouds of the day over the high mountain peaks and ridges, while cloud formation over the lower areas of South Park was inhibited for about 2 h. It is interesting to note that a similar phenomenon occurred over a much larger area on a time scale of 6–12 h; deep thunderstorms occurred over the mountainous areas of Colorado before 1300 MDT, while all cumulus convection was inhibited over the plains of eastern Colorado for several more hours. In this section the period of development and transition from a group of mountain thundershowers to a developing High Plains mesoscale convective system is documented using radar and PAM surface data.

The 1301 MDT South Park sounding (Fig. 17) shows the influence of this mountain thunderstorm activity on the South Park environment. Downdrafts from the first precipitating cumulus clouds which passed near the CSU base served to stabilize the lowest 5 kPa (0.6 km AGL). Above this, the well-mixed neutral layer extended to 51 kPa, with light winds veering from 170° to 280°. A deep mid- to upper-level tropospheric layer (45–25 kPa) continued the substantial moistening and slight warming trends that were evident from the earlier soundings (Figs. 10 and 15) and winds in the upper troposphere (above 35 kPa) continued to back.

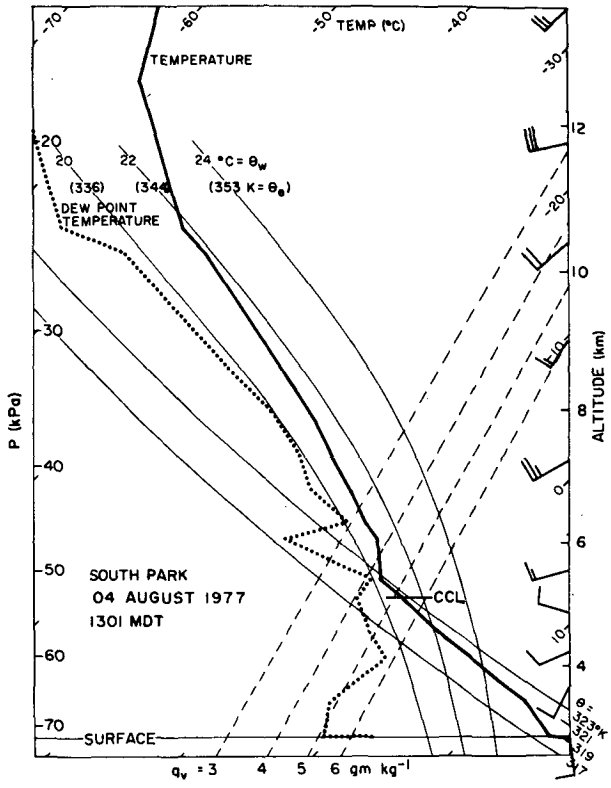

FIG. 17. South Park sounding of 1301 MDT 4 August 1977 (as in Fig. 10).

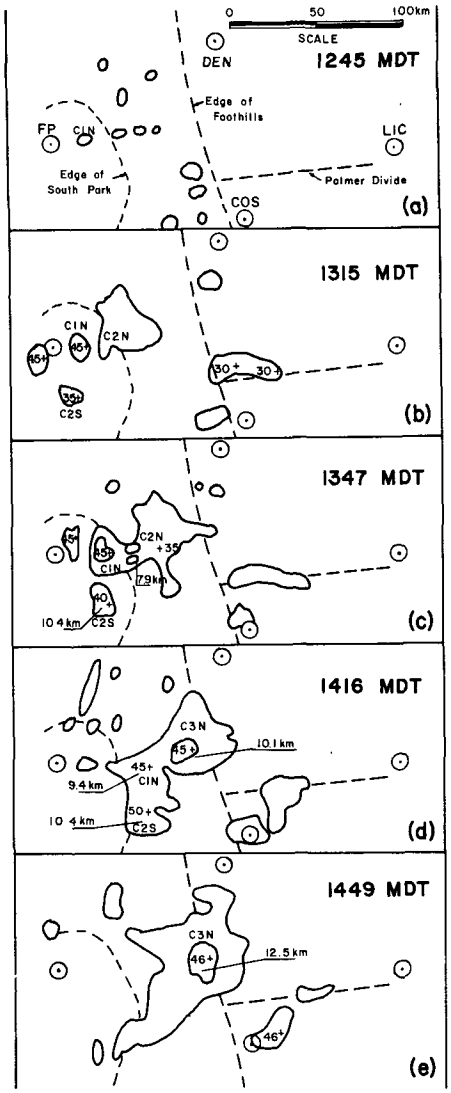

FIG. 18. Composite radar summaries from the region between Fairplay (FP) and Limon (LIC). Outer contour is minimum detectable signal at Limon NWS radar. Inner reflectivity contours [40 dB(Z)], intensities of cell cores [dB(Z)] and echo tops (km MSL) are derived from composited Limon, CP-3 and CBS-4 radar data. Cells referred to in text are labeled. Dashed lines denoting South Park and foothill boundaries and Palmer Divide are qualitatively based on the more detailed topography in Fig. 1. Summary times are (a) 1245 MDT, (b) 1315 MDT, (c) 1347 MDT, (d) 1416 MDT and (e) 1449 MDT, 4 August 1977.

These features reflect the thermal advection pattern and the passage of the weak upper-level ridge, along with continued mid-level moisture advection from the west, as discussed in Section 3.

A sequence of radar summaries (Fig. 18) shows that deep convection was widespread and growing rapidly by this time. Included in the summaries are the outline of the minimum detectable signal (TRW−) at Limon, combined with composited reflectivity and echo top data from the Limon radar, NCAR/CP-3 radar and CSU/CBS-4 radar. This sequence provides an overview which shows that in a span of about 2 h, the South Park and foothills convection had combined and organized into a large cumulonimbus system as it began entering the High Plains.

Focusing more closely on South Park, a PAM/CP-3 depiction (Fig. 19) for 1254 MDT shows one member of an east–west line of cells, here designated C1N, at the north end of the Park. This cell had a reflectivity of over 40 dB(Z), while another cell in the Mosquito Range southwest of the base (C1S) was just starting to intensify. Downdraft gust fronts from both of these cells appear in the surface data, with winds shifting to west or southwest behind the fronts, temperatures decreasing, and mixing ratios increasing slightly.

Cumulonimbus development proceeded rapidly after 1300 MDT. By 1316 MDT (Fig. 20) CP-3 radar showed two large cells near the base. The southernmost cell was in the process of splitting into two cells, C1S and C2S, both associated with the downdraft gust front which had passed the base by 1255 MDT (Fig. 19). The combined radar summary for 1315 MDT (Fig. 18b) shows three strong cells in South Park. The northernmost two cells, including C1N, lined up east to west with a rapidly expanding precipitation area, labeled C2N, in the Front Range northeast of South Park, a

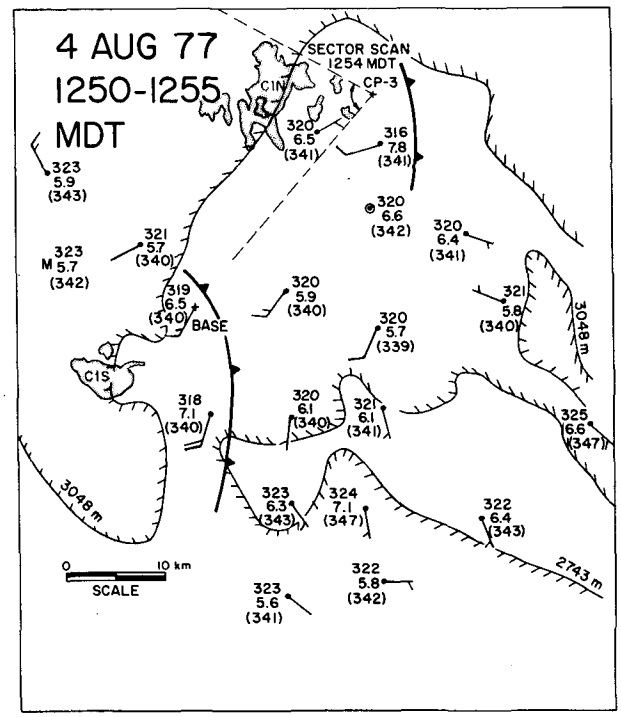

FIG. 19. Composite PAM/CP-3 radar plot for 1250–1255 MDT 4 August 1977. Surface data and terrain contours are as in Fig. 11. CP-3 data are from a 5.5° constant-elevation scan at 1254 MDT, projected onto a horizontal surface. Light and dark shading denotes echo reflectivities exceeding 25 and 40 dB(Z), respectively. Cold front symbol denotes a gust front or mesoscale cold front.

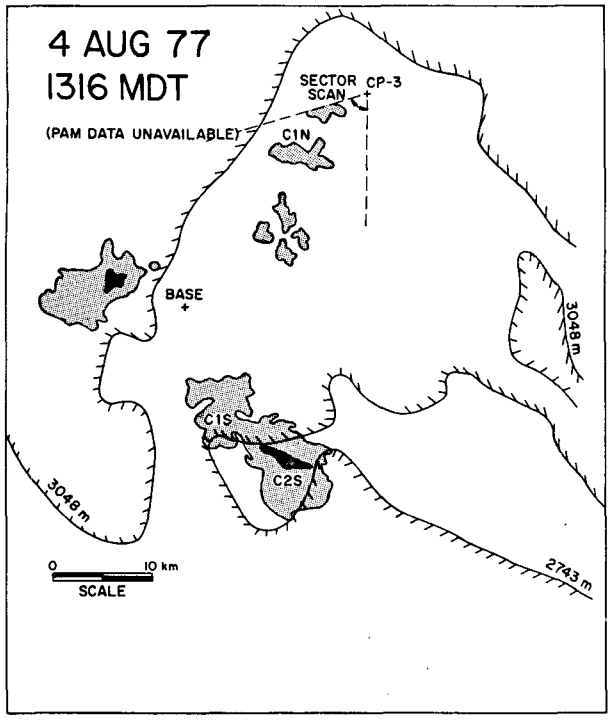

FIG. 20. CP-3 radar reflectivity contours for 1316 MDT 4 August 1977. Reflectivities are as in Fig. 19. (PAM data not available at this time).

climatologically favored area for echo development (Karr and Wooten, 1976; Henz, 1974). A line of cells had also formed from near Colorado Springs northeastward onto the Palmer Lake Divide.

The nature of the cold outflow behind the cells in South Park is indicated in Fig. 21 for 1336 MDT. Winds behind the gust front location were northwesterly, switching to due north further west of cell C2S. Note the strongly divergent flow between the northerlies behind cell C2S and the southwesterlies behind cell C1N and under the decaying cell near the base. Reduced θ_e values in this divergent flow (as low as 336 K east of the base), as well as in the chilled air in the lowest 5 kPa of the 1301 MDT sounding (Fig. 17), indicate that this air was probably entrained from the environmental west–southwesterly flow in the 50–45 kPa layer, about 2 km above the Mosquito Range ridgeline. This basic pattern of very coherent northerlies behind cell C2S and southwesterlies behind cell C1N persisted and expanded eastward through the next hour, during which the two cells propagated eastward out of the Park and interacted with the Front Range convection.

At 1336 MDT, CP-3 radar indicated that cell C1N had intensified and was the strongest cell in South Park (Fig. 21). By 1347 (Fig. 18c) cell C1N had expanded and begun merging eastward into the large echo in which the developing cell C2N was embedded, creating a meso-β-scale convective cluster. Cell C2S propagated across the eastern edge of South Park in a continuous fashion from a westerly direction (260°) at about 10 m s^{-1} until 1416 (Fig. 18d), when it began to merge on the southern flank of cell C1N, thereby expanding the meso-β cluster. At this time, most convection had left South Park, and new growth was concentrated over much lower terrain of the Platte River Valley south of Denver (refer to Fig. 1).

Northeast of cell C1N, and apparent on the 1416 MDT radar summary (Fig. 18d), the third and most important cell of this sequence, cell C3N, had grown and intensified rapidly to over 45 dB(Z), and was located at the eastern edge of the Front Range foothills. In contrast, no new growth was apparent east of cell C2S. It may be significant that the surface winds in northern South Park, under the evolving thunderstorms, had a strong westerly component, while those to the south did not. This could have created enhanced low-level convergence in regions east of northern South Park, aiding the process of discrete eastward propagation which took place there.

After 1416 MDT, the area of strong cumulonimbus development had shifted completely to the High Plains/Front Range interface. South Park radar echoes had dissipated rapidly, with the northern sequence of cells disappearing earliest. The focus of cumulonimbus activity on the Front Range was at cell C3N, the third of the northern sequence of cells. This large storm was the first echo of the day to extend to near the tropopause (12.5 km as observed by CBS-4 radar). This cell was

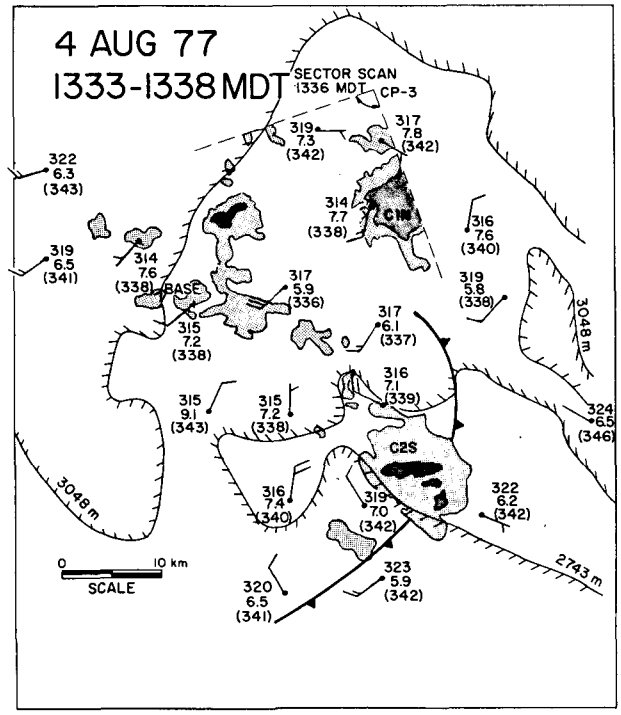

FIG. 21. As in Fig. 19, except for 1333–1338 MDT 4 August 1977. Reflectivity contours are for 1336 MDT.

observed by both radar (Fig. 18e) and satellite to be moving faster than the small, intense cells emanating from the Colorado Springs area. Isolated cells had more recently developed along the Front Range northward into Wyoming and southward into New Mexico, but both satellite and Limon radar indicated that the mesoscale cluster in Fig. 18e was the dominant system in the region.

6. Afternoon evolution of the High Plains mesoscale storm complex

During the mid-day evolution of mountain thunderstorms, convection over the High Plains was suppressed in a manner somewhat analogous, but larger in scale, to the suppression of early morning convection seen previously over South Park. Objective surface analyses, limited to the plains region east of the Rockies (the analysis technique and the reasons for this limitation are discussed in the Appendix), reveal a basically downslope drainage flow over eastern Colorado at 0600 MDT 4 August (Fig. 22), similar to the concurrent smaller-scale drainage flow over South Park in Fig. 11. The mesoscale features depicted in Fig. 22 and in subsequent objective analyses are taken directly from the mesoscale pressure analyses in Fig. 5. Significant features in Fig. 22 include the meso-high and divergent outflow in southeastern Kansas associated with the decaying first MCC of the episode, the first cool surge approaching Colorado from the north and the trough extending from New Mexico into western Kansas. In eastern Colorado ahead of the front, the westerly downslope flow, on closer examination, is seen to be draining into the South Platte and Arkansas River valleys to the north and south, respectively, of the Palmer Divide. This is evident in the 1° × 1° gridded terrain (compare with the more detailed topography of Fig. 1).

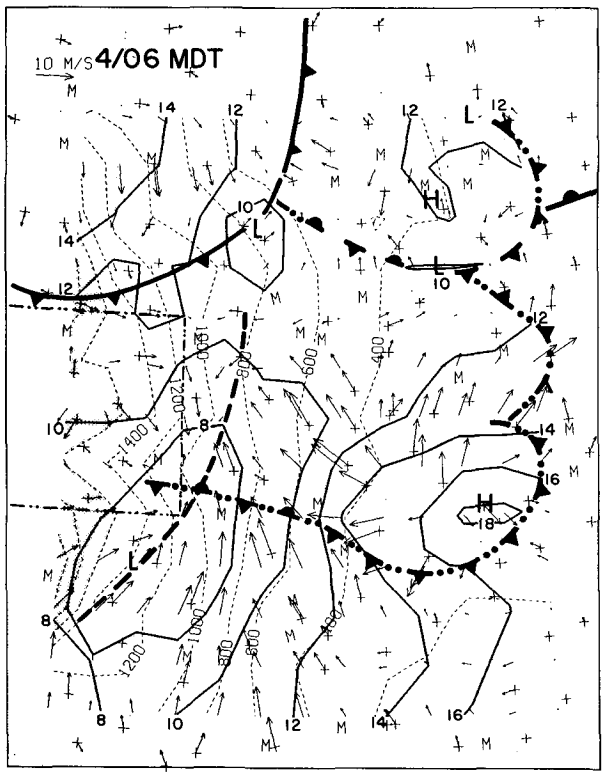

FIG. 22. Regional-scale objective surface analyses (see Appendix for details) over the Great Plains at 0600 MDT 4 August, for sea-level pressure (heavy contours, 10^{-1} kPa − 1000), winds (tails at grid points) and terrain height (thin dashed contours, m). Observed winds are plotted with the plus symbols at the station locations (M denotes missing). All winds are proportional to the 10 m s^{-1} key vector in the upper left. Terrain higher than 1600 m is shaded (more detailed topography for eastern Colorado is shown in Fig. 1). Mesoscale features are from Fig. 5e.

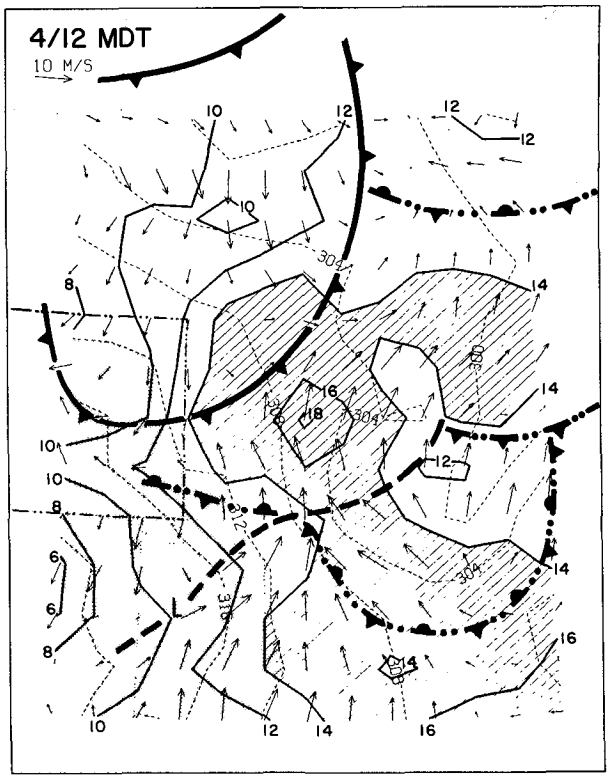

FIG. 23. Regional-scale objective surface analyses for 1200 MDT 4 August. Gridded winds are as in Fig. 22. Heavy contours are q (g kg^{-1}, hatched for ≥14 g kg^{-1}). Thin dashed contours are θ (K, shaded for >312 K). Mesoscale features are from Fig. 5g.

By 1200 MDT (Fig. 23) the weakening front had reached east-central Colorado, where it apparently stalled in the region of the Palmer Divide and became indistinguishable in the SPACE/HIPLEX surface observations on the High Plains (see Fig. 1). South of the front in the Arkansas Valley, easterly upslope flow had developed, beginning at about 1000 MDT, consistent with the mean diurnal wind patterns described by Johnson and Toth (1982). From the isopleths of θ and q, this flow is seen to be advecting potentially cool,

moist air up the valley, analogous to the cool, moist advection that was established by 1000 MDT over South Park (Fig. 14). North of the front, the northerly flow had developed an easterly component, possibly reflecting a diurnal upslope component. The potentially cool advection associated with the cool surge in northeast Colorado, along with the cool, upslope advection south of the front, suppressed the development of convective activity over eastern Colorado while mountain thunderstorms were occurring. The flow behind the front had been a dry advective pattern throughout the morning, with q values decreasing by 1–2 g kg^{-1} in northeast Colorado. However, the moist, easterly advection south of the front had increased q in the Arkansas Valley south of the Palmer Divide by 1–2 g kg^{-1}, resulting in the moist tongue seen at 1200 in Fig. 23. Note also the large q values in central Kansas. These were due to heavy rains from the previous evening's MCC and provided an abundant moisture source for the second MCC.

It was shown in the previous section that the first intense, eastward-propagating cumulonimbus cell to appear on the High Plains had its evolutionary and probably also its dynamic origins in an earlier series of mountain thunderstorms in northern South Park (Fig. 18). At about 1500, rapid growth and intensification of this cluster ensued at the western edge of the plains, concentrated on the northern and southern flanks of the Palmer Divide. The 1500 surface environment into which the cluster was building was characterized by continued easterlies south of the stalled front and northeasterlies to the north (Fig. 24). The axis of maximum θ_e extending westward up the Arkansas Valley from western Kansas reflects the warmer, moister air to the south of the Palmer Divide.

Kinematic fields computed from the gridded surface winds (not shown) reveal fairly coherent bands of convergence and positive vorticity in association with the front as it moved into Colorado. The magnitudes were rather weak, however, relative to the convergence and vorticity in the Oklahoma panhandle region associated with the trough extending from New Mexico. At the onset of convective intensification over the High Plains, weak convergence (and moisture convergence) extended over the Palmer Divide and into northeastern Colorado, and the vorticity signal was very weak.

Although the front undoubtedly contributed to low-level afternoon convergence over eastern Colorado, its effects are difficult to separate from the purely diurnal, topographically-induced convergence over the Palmer Divide. The existence of mean summer afternoon, low-level convergence over the Palmer Divide, and over other High Plains ridges extending eastward from the Rocky Mountain plateau, can be inferred from a number of studies (Wetzel, 1973; Karr and Wooten, 1976; Johnson and Toth, 1982). Given the observation density, objective analysis resolution and uncertainties in the analyses particularly near the western boundary

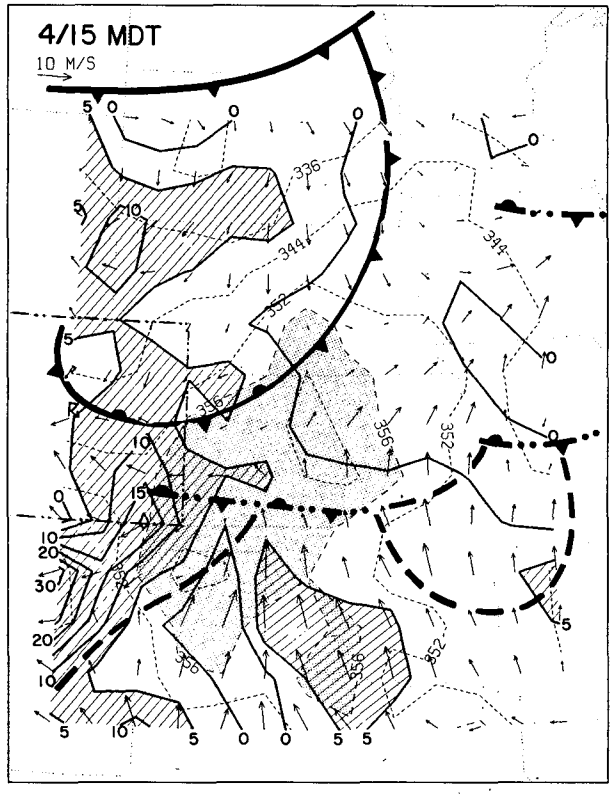

FIG. 24. Regional-scale objective surface analyses for 1500 MDT 4 August. Winds are as in Fig. 22. Heavy contours are terrain-induced vertical motion (mm s^{-1}), with regions exceeding 5 mm s^{-1} hatched. Thin dashed contours are θ_e (K), with areas within the intermediate 356 K contour shaded. The thunderstorm symbol denotes the location of the first intense cumulonimbus cluster to reach the High Plains at about this time. Mesoscale features are from Fig. 5h.

(see Appendix), however, the divergence field on the scale of these meso-β terrain features is much less resolvable than the general upslope flow field over eastern Colorado. Computing terrain-induced vertical velocity as $\mathbf{V} \cdot \nabla h$, where h is the gridded terrain height in Fig. 22, Fig. 24 shows a coherent upward-motion region of 0.5–1.5 cm s^{-1} over the entire High Plains from Wyoming to New Mexico. This meso-α-scale terrain-induced forcing, enhanced by meso-β-scale terrain-induced convergence over the Palmer Divide and by frontal-associated convergence in the same region, provided focused, low-level environmental lifting over the High Plains in which the mountain-generated convection could develop upscale. We now follow the meso-β-scale evolution of the convective system for the remainder of 4 August. The IR satellite sequence at approximately 1 h intervals in Fig. 25 provides an overview of the evolution.

A surface analysis on the SPACE/HIPLEX scale for 1500 MDT, superimposed with the 1530 MDT Limon radar summary (Fig. 26), shows strong easterly inflow into the region of rapid cumulonimbus intensification,

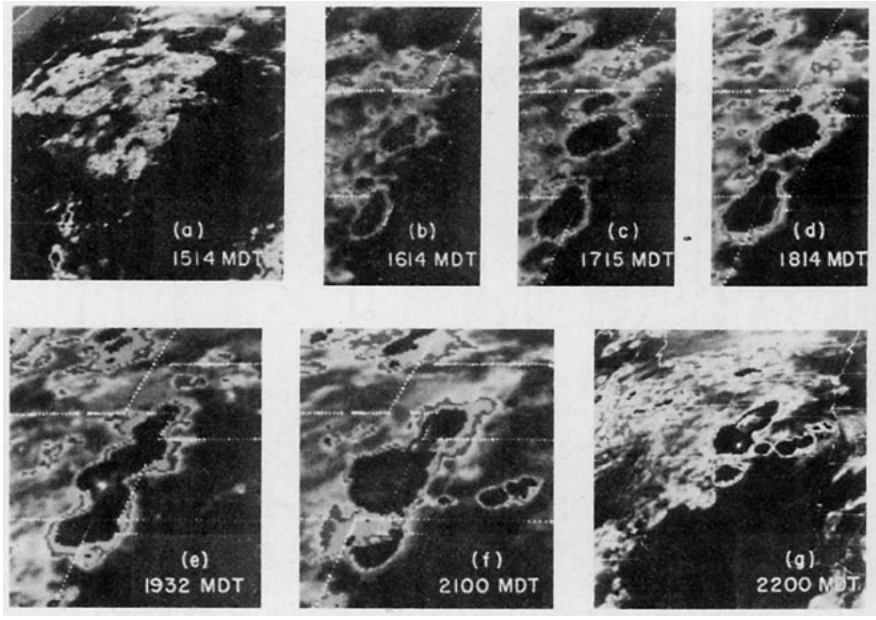

FIG. 25. IR satellite images, centered near eastern Colorado, on 4 August 1977, for MDT times (a) 1514, (b) 1614, (c) 1715, (d) 1814, (e) 1932, (f) 2100 and (g) 2200. The first and last images, at one-half the scale of the others, provide more extensive views of the storm system's environment. Gray shades are as in Fig. 4. Temperatures colder than −63°C (lighter shades within interior black contours) indicate convection reaching or penetrating the tropopause, which is at 13.2 kPa (15.0 km) based on the 1700 MDT Limon sounding.

which spanned across Palmer Divide. (Table 1 relates the Limon radar echo contours to various descriptors of storm intensity.) Topographic forcing associated with the frontal-enhanced northeasterly flow north of the divide may be partly responsible for a small tornado that was spawned at about 1545 by the intense cell southeast of Denver in Fig. 26. This cell had the coldest IR top at 1514 (Fig. 25a). However, coherent southeasterly upslope winds and higher mixing ratios (11–12 g kg^{-1}, with $\theta_e > 350$ K) in the Arkansas Valley to the southeast of the cluster, compared to less coherent winds in the Limon area and drier air (<10 g kg^{-1}, with $\theta_e < 345$ K) along and north of the Divide, produced the strongest moisture advection on the southeastern flank of the cluster. Thus, the strongest cumulonimbi were subsequently observed along the southern slopes of the divide.

After 1530 MDT, a solid mass of thunderstorms with an expanding anvil cloud shield (Figs. 25b, c) proceeded east–southeastward from the Colorado Springs area. Limon radar resolved this mass into at least four separate storms, each with intensities of over 50 dB(Z). Surface winds behind this group of cells were strong from the north, just as in South Park earlier in the day, while winds ahead of the cells were easterly or southeasterly at 5 m s^{-1}. These storms produced up to 18 mm of rain close to the foothills and 29 mm was reported to the southeast, along the southern slopes of the Palmer Lake Divide (Fig. 27).

By 1700 (Fig. 27), the most severe convective cells (TRWXX, with hail signatures) were located in the moist surface air south of Limon. A broad lower-intensity echo region extended northward and eastward from these cells to cover almost all of the Palmer Lake Divide area . An expanding, rain-chilled surface mesohigh had developed beneath the echo shield. The eastern edge of this echo region extended to 35 km east of Limon, as confirmed by data from the Goodland HIPLEX radar (dash-dot line in Fig. 27). Southeast of Limon, a heavy thunderstorm (TRW+) embedded in an echo region about 40 km in diameter was observed from Goodland, but not from Limon, indicating that no precipitation from this storm had yet fallen low enough to enter the Limon radar's very low (0.5°) scan. Another heavy thunderstorm northeast of Denver was part of another large echo mass which was separate from the Limon storm, but which seemed to be propagating in a similar manner. The IR image of 1714 (Fig. 25c) indicated that this separate cluster, while being appreciably large, had not produced overshooting convective debris as cold, nor a cold cloud-top shield as extensive, as the more intense cluster over Limon. Note the intense cluster to the south of the study area in northeastern New Mexico which is comparable to the Limon cluster. By this time, thunderstorms in the mountains were mostly small and scattered.

The dominance of storm-scale and mesoscale dynamics over the larger-scale ambient flow is clearly

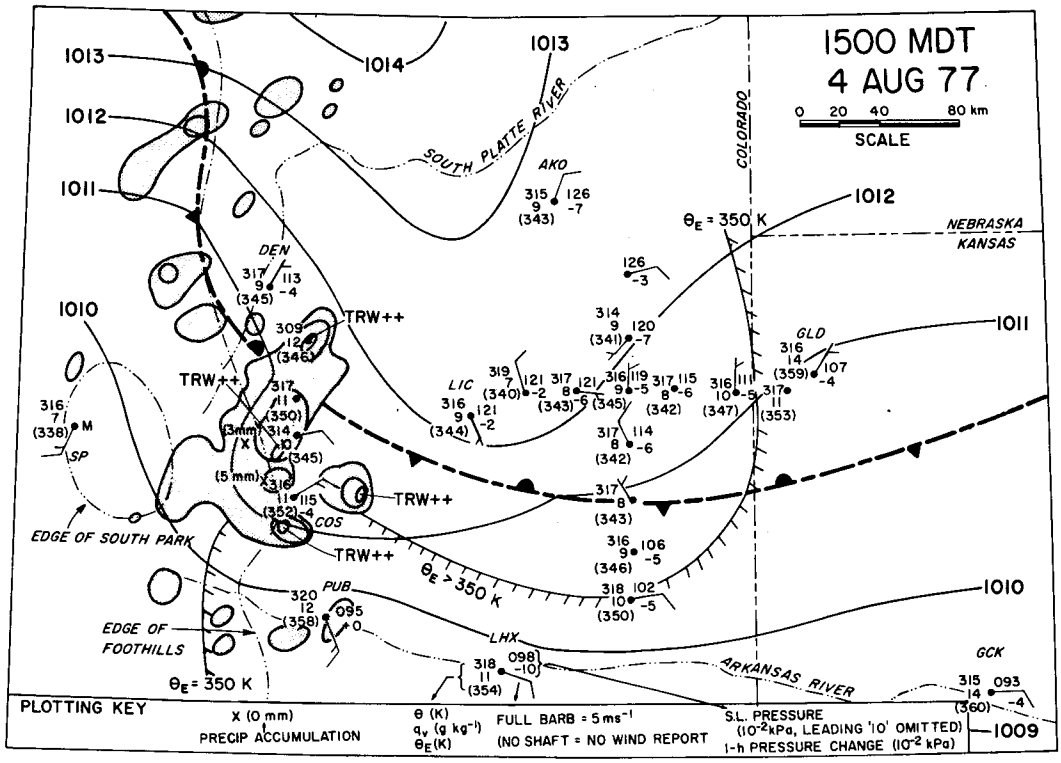

FIG. 26. SPACE/HIPLEX surface analysis for 1500 MDT 4 August 1977, superimposed with Limon radar summary for 1530 MDT. Dash-dot lines indicating South Park and foothills boundaries are based on the more detailed topography in Fig. 1 (Palmer Divide, which extends from LIC westward to the foothills, is omitted for clarity; see Fig. 1). Experimental mesonet data are plotted at the unlabeled locations marked in Fig. 1. Supplemental data from standard hourly observations at Denver (DEN), Colorado Springs (COS), Limon (LIC), Akron (AKO), Fort Collins (FCL), Pueblo (PUB) and LaJunta (LHX), Colorado; from Goodland (GLD) and Garden City (GCK), Kansas; and from beyond the map boundaries were also used in the analysis. Winds, potential temperature, mixing ratio, equivalent potential mixing ratio, pressure reduced to sea level and 1 h pressure changes are plotted according to the key in the figure. Altimeter settings from the standard observations were reduced in a manner consistent with the experimental pressures (diurnal effects are not removed). Isobars are analyzed at intervals of 10^{-1} kPa. Successive radar echo contours (beginning with No. 1) and maximum thunderstorm intensity designations are described in Table 1. Hatched line separates region to the south and east which has θ_e exceeding 350 K. Precipitation values (mm) are 1 h accumulations ending at map time, based on a sparse hourly recording network.

evident from a mesoscale east–west cross section for 1700–1800 MDT (Fig. 28). Soundings from Limon and Goodland at 1700, South Park and Grand Junction at 1800, and an east-to-west aircraft flight which passed over Limon at about 1740 were used in this cross section.

At Goodland, ahead of the storm system, the moist planetary boundary layer was still capped by a sharp inversion and drop in mixing ratio at 2.2 km AGL. The Goodland sounding had a Total Totals index (Miller, 1967) of 58 and a 50 kPa Lifted Index (LI) of −4.5°C, both very unstable. However, the inversion at the top of the PBL prevented the immediate release of this instability by means of cumulus convection.

The contrast between the Limon and Goodland soundings reveals the strong gradients in temperature, moisture and vertical structure across the radar echo boundary. In the lowest 2 km, a θ-gradient of over 3 K existed between Limon and Goodland, probably due to weak cool advection in the northeasterly flow at low levels over Goodland. This flow was enhanced by the low-level trough associated with the weak front that had earlier entered Colorado. Between 70 and 50

TABLE 1. Relationships of Limon NWS radar summary contour number and storm descriptors (TRW−, etc.) to echo reflectivity and expected surface rainfall rate. Rainfall rate is only approximate and may be a function of many other variables besides reflectivity.

Contour number	Radar summary description	Reflectivity [dB(Z)]	Rainfall rate at surface (mm h^{-1})
1	TRW−	15–30	<3 light
2	TRW	30–41	3–13 moderate
3	TRW+	41–46	13–25 heavy
4	TRW++	46–51	25–51 very heavy
5	TRWX	51–57	51–127 severe
6	TRWXX	>57	>127 extreme

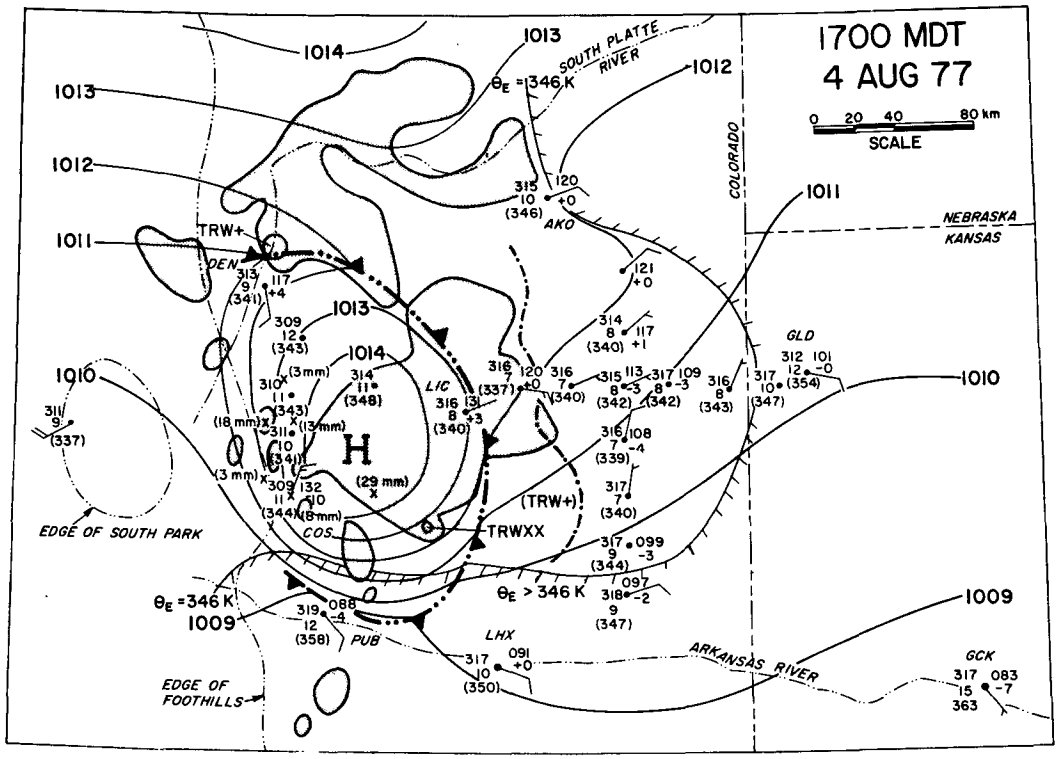

FIG. 27. Similar to Fig. 26, but for 1700 MDT 4 August 1977. The weakening front drawn in Fig. 26 has been dropped, with a mesohigh boundary now included. Bold dashed-dotted line denotes the easternmost edge of the 20 dB(Z) Goodland radar echo from elevation 1–12°. Hatched line delineates high θ_e air (>346 K) to the south and east. Precipitation values are 2 h accumulations ending at map time (since Fig. 26).

kPa, a strong moisture gradient existed between the moist cloud layer over Limon and the much drier air above the Goodland inversion, much sharper than the moisture front suggested earlier further west (Fig. 6). Above 46 kPa, a strong θ gradient, as large as 7 K, had developed between Limon and Goodland. This gradient was partly produced by slight upper-level cool advection at Goodland by steady west–northwesterly flow (resolved by four soundings over the last 12 h), combined with mid- to upper-level warm advection at Limon and to the west. The anticyclonic wind field is indicative of the ridge that had earlier passed through South Park (as evidenced by backing sounding winds with time) and which was by now near Limon.

Cold, stable outflow air near the surface occupied the region to the west of Limon at 1700 MDT. This region, bounded by a bold line on the cross section (Fig. 28), is the top of a surface-based inversion observed at South Park. Aircraft vertical-motion measurements at 55 kPa indicate subsidence extending from South Park to Limon, with the strongest subsidence being near Limon, just west of the northerly wind area at 56 kPa.

The rapid eastward propagation of the convective system can be seen by comparing surface and radar observations from 1800 MDT (Fig. 29) with data from one hour earlier (Fig. 27). The radar echo front east of Limon moved eastward at 15 m s^{-1} during this hour. All stations in eastern Colorado reported pressure beginning to rise, with the largest 1 h rises occurring 50–90 km behind the echo front. Although the edge of the precipitation echo was already 90 km east of Limon, no precipitation was observed before 1800 MDT anywhere east of Limon. In fact, total precipitation for the entire day over the mesonet east of Limon was only 3–5 mm. A similar, lightly precipitating storm system was moving on a parallel course about 50 km north of the Limon system. The northerly wind shift at Denver, along with subsequent northwesterly shifts progressing southeast into the mesonet, suggests an independent mesohigh associated with the northern cluster, despite its weaker echoes and satellite appearance (Fig. 25d). The most intense thunderstorms were found in the Arkansas Valley, 50–100 km south of Limon. The greater intensity of these storms was a consequence of the presence of larger amounts of low-level moisture to the south.

Objective surface analyses for 1800 (Fig. 30) show the larger-scale features in relation to the mesoscale convective systems on the High Plains. Chilled (Fig. 30a), divergent (Fig. 30b) regions are seen to the rear of the mesoscale systems in eastern and northeastern

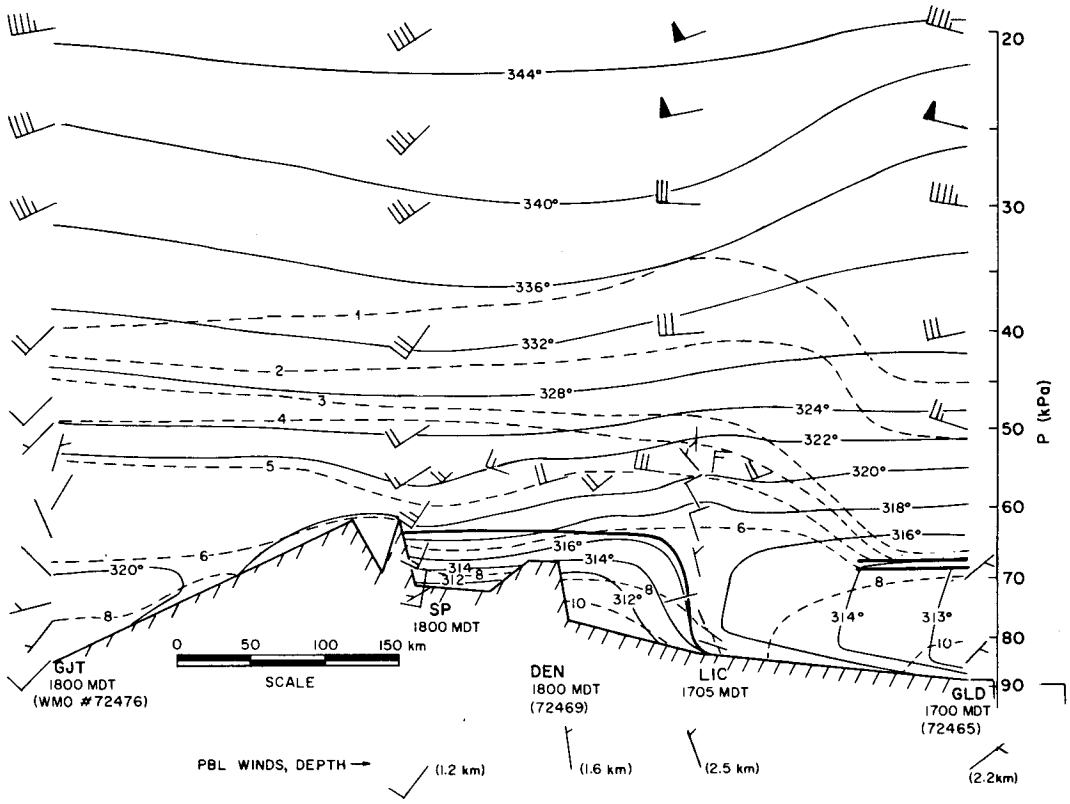

FIG. 28. East-west cross section including soundings from Grand Junction (GJT), South Park (SP) and Limon (LIC), CO and Goodland (GLD), KA and an east-to-west aircraft flight near 55 kPa (passed over LIC at 1740 MDT), for 1700–1800 MDT 4 August 1977. Solid contours are θ (K), and dashed contours are q (g kg^{-1}). A full wind barb represents 5 m s^{-1}. Terrain and stable layer boundaries are marked with bold lines. PBL average winds and depths are plotted below each station for SP, LIC, GLD, and Denver (DEN).

Colorado (depicted here as a single meso-high boundary), as well as with the separate system in northeast New Mexico. Ahead of the meso-high boundaries lies an arc of strong convergence with maxima in eastern New Mexico, in the Oklahoma panhandle, and on the Colorado/Kansas border. Just ahead of the eastward-propagating convergence arc is an arc of strong terrain-induced vertical motion, with maxima exceeding 1 cm s^{-1} in northwest Kansas and western Oklahoma. Thus, with the convective systems propagating into moister regions (Fig. 30a) and with strong low-level forcing present, further intensification was imminent.

Because of the strong easterly moisture advection in western Kansas (Fig. 30a), subsequent convective intensification became most pronounced in that region rather than in the areas of comparable low-level forcing to the south. By 2100 (Fig. 25f), a line of more intense convective activity had developed near the Colorado/Kansas border extending north from Goodland. Surface data throughout most of the day had shown a strong west-to-east moisture gradient in this region, with surface mixing ratios of 7–8 g kg^{-1} to the west and as high as 14 g kg^{-1} to the east of this area. The highest values of θ_e had persisted to the south, east and northeast of the Palmer Divide (see Figs. 26–29). Radar and satellite data in previous figures document the migration of the relatively weak mesoscale storm system from the region of the Front Range north of Denver toward the northeastern Colorado border during the day. After 1900, this system began to intensify as it encountered enhanced low-level moisture and formed a very coherent line of intense thunderstorms (Fig. 25e).

By 2100 MDT, the meso-β surface/radar analysis (Fig. 31) shows that this line was approaching Goodland with reflectivities of over 60 dB(Z) and echo tops of at least 15.5 km. A region of northerly winds in cold, moist air extended at least 180 km west from the thunderstorm line, repeating the pattern of northerly outflow winds behind convective regions, seen on smaller scales in South Park and the Front Range earlier in the day.

IR satellite data confirm the rapid intensification of the relatively narrow north–south line of storms near Goodland at 2100 MDT (Fig. 25f) into the system with the coldest anvil outflow on the plains by 2200 MDT (Fig. 25g), with a simultaneous decrease in intensity of the storms over the Arkansas valley.

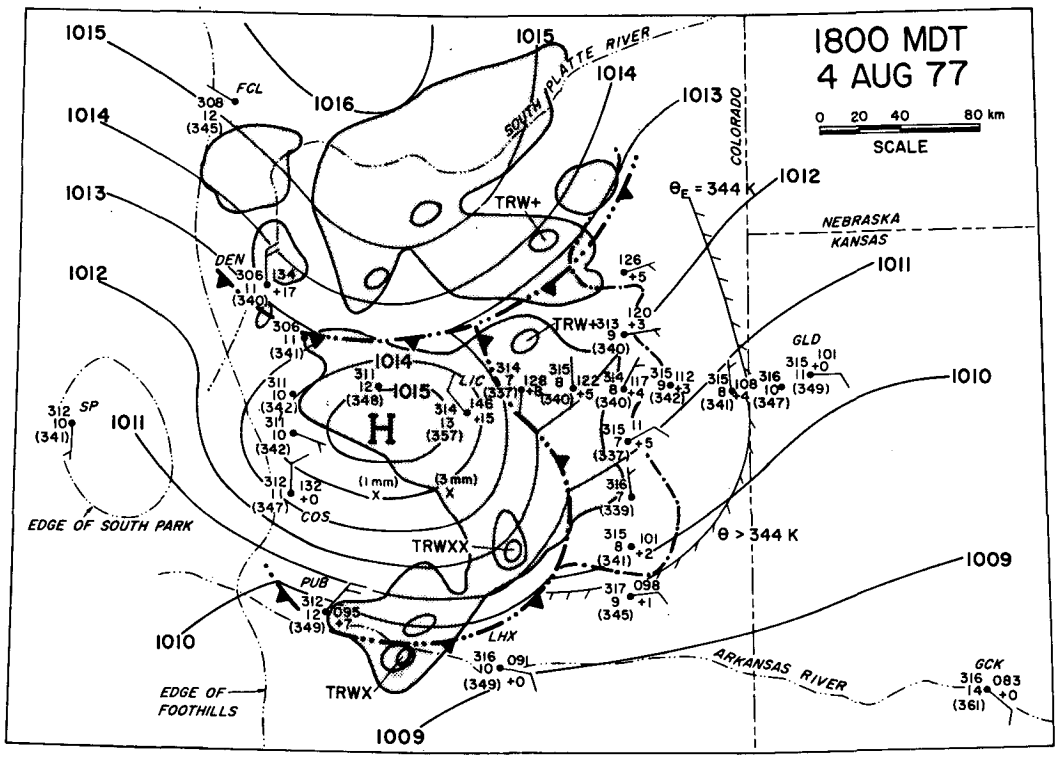

FIG. 29. As in Fig. 27, except for 1800 MDT 4 August 1977. Hatched line delineates high θ_e air (>344 K) to the south and east. Precipitation values are 1 h acccumulations ending at map time (since Fig. 27).

7. Summary and conclusions

The pattern of convective activity which evolved on 4 August 1977 closely obeys the observed mean climatological patterns that have been described previously (Karr and Wooten, 1976; Henz, 1974; Dirks, 1969; Wetzel, 1973; Crow, 1969; Wallace, 1975). Included among these patterns are the growth of the first cumulus clouds over the highest peaks; the formation of precipitation cells over certain "hot spots"; propagation of mountain thunderstorms eastward with the prevailing winds; preference of early storm development for the Palmer Lake Divide area south of Denver, Colorado; intensification of the mesoscale storms upon passage into regions of greater low-level moisture; and widespread nocturnal thunderstorm activity in the central Great Plains, with an eastward progression of the precipitation maximum with time. August 4 was the second of a series of eight consecutive days on which mesoscale convective complexes (MCCs) formed on the High Plains and moved eastward through the region as nocturnal storms.

A brief time sequence of events helps emphasize the most significant findings of this case study. The first phase shows the evolution of the morning boundary layer over the elevated mountain basin of South Park. Shortly after sunrise, very small-scale slope winds began in the lowest 50 m of the atmosphere. After 2 h, a larger-scale valley wind commenced in the South Platte Valley. This cool advection helped suppress the growth of a deep PBL over South Park until about 1200 MDT. Over the higher peaks, however, a deep mixed layer allowed cumulus cloud formation by 1000 MDT. These small cumuli appeared to eliminate an inversion at 48 kPa, allowing deep precipitating clouds to form by 1200 MDT.

The second phase began as convective precipitation echoes appeared on radar at 1220 MDT, tending to occur initially over certain "hot spots". Two groups of these cells began to propagate rapidly eastward at 1300, in association with westerly surface gust fronts. The cells in northern South Park formed a line of discrete cells which propagated eastward to the edge of the High Plains, where the storm rapidly intensified to severe levels. A north–south line of strong thunderstorms began to form at the edge of the plains after 1430, spawning a tornado.

The third phase commenced as this mesoscale squall line began to propagate eastward across the Palmer Lake Divide. The northern part of the line became less intense as it crossed the Limon area, which was somewhat drier in the lower levels, with lower θ_e values, than in the Arkansas Valley to the south. The convection maintained a linear shape and continued to

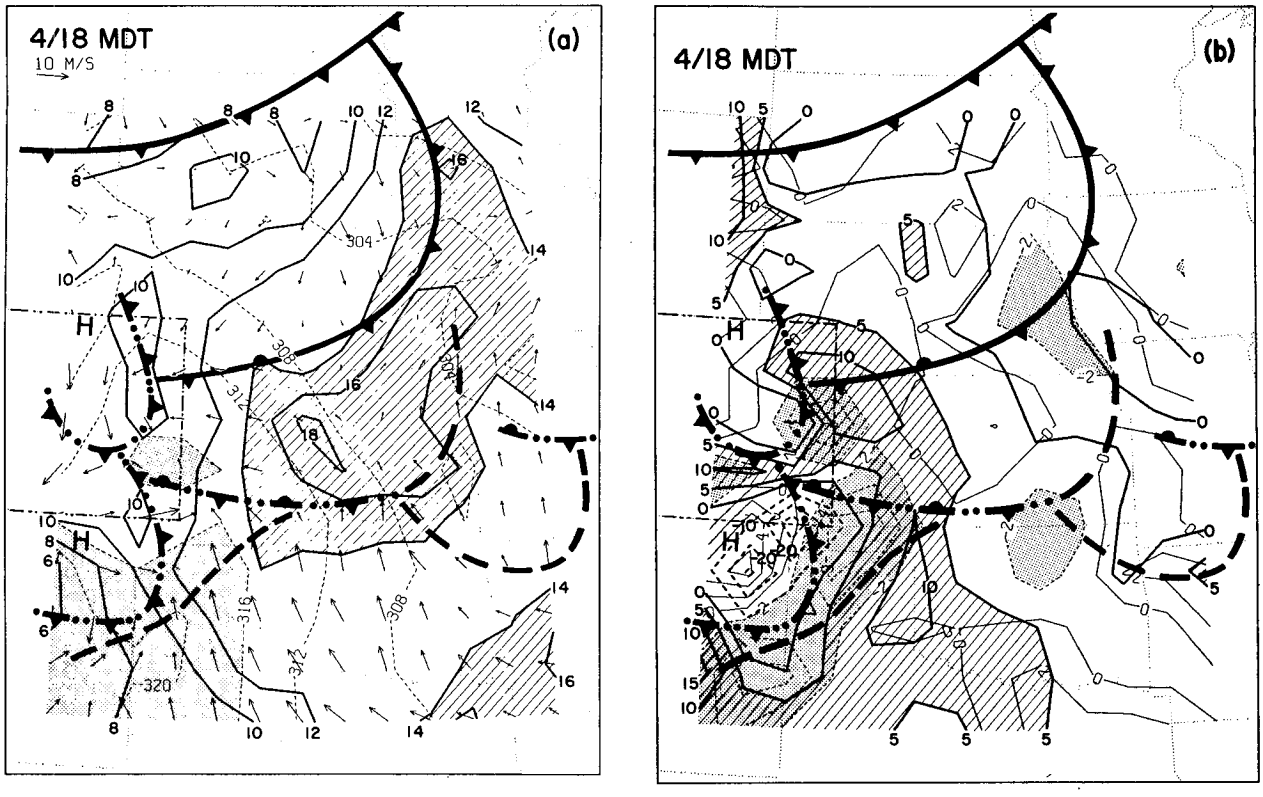

FIG. 30. Regional-scale objective surface analyses at 1800 MDT 4 August for (a) winds, θ and q (conventions as in Fig. 23, except shading is for $\theta > 316$ K) and for (b) terrain-induced vertical motion [heavy contours (solid) and at 5 mm s^{-1} intervals for non-negative values (dashed) and at 10 mm s^{-1} intervals for negative values (hatched where exceeding 5 mm s^{-1})] and divergence (thin contours, 10^{-5} s^{-1}, dashed for negative values, shaded where $< -2 \times 10^{-5}$ s^{-1}). Mesoscale features are from Fig. 5i.

move rapidly eastward. Most of northeastern Colorado, despite being crossed by an active convective line, received very little precipitation, a common result in this semi-arid region. At about 1900, the thunderstorms in northeastern Colorado rapidly intensified to severe levels as they encountered greater low-level moisture near Goodland, Kansas. Prior to the propagation of the convective line over eastern Colorado, convection over the plains had been suppressed in a manner analogous to the suppression of cumulus development over South Park in the morning. The Goodland storms produced in excess of 50 mm of precipitation over large areas as they continued eastward to help form a large nocturnal convective complex over the central plains, discussed in Part II.

Some striking similarities have been noted in the dynamic behavior of the 4 August mesoscale system as it grew from a scale of 10 km over South Park to a sprawling complex on a scale of 1000 km over the High Plains. Circulation features which seemed to be reproduced over a wide range of scale include:

1) The nocturnal pooling of stable air in the lower lying areas led to a suppression of cumulus development over South Park until 1200 MDT and the suppression of thunderstorms over the eastern Colorado plains until after 1500.

2) The less stable air over the high mountain peaks and ridges was rapidly heated to form the first cumulus clouds of the day; similarly, deep thunderstorms first occurred over the Colorado mountain barrier before 1300.

3) The northerly flow to the west of individual thunderstorms over South Park was also found to the west of squall lines over the eastern Colorado plains, perhaps induced by the ambient larger-scale pressure gradient.

The favoring of early cumulonimbus convection over the north–south oriented mountain barrier while convection over the plains is suppressed early in the day, is a major factor in contributing to the formation of a temporally coherent mesoscale convective system whose north–south extent is several hundred kilometers. The major dynamic factors contributing to the eastward propagation of this system can only be inferred from these observations. Certainly, the existence of a "density current" (see Moncrieff and Miller, 1976) fed by the cool low-level outflow from a number of large thunderstorm cells could be seen in the observations over the South Park area and over portions of the High Plains. Under the prevailing southwesterly flow, one would expect a density current to favor the formation of a generally downsloping, easterly prop-

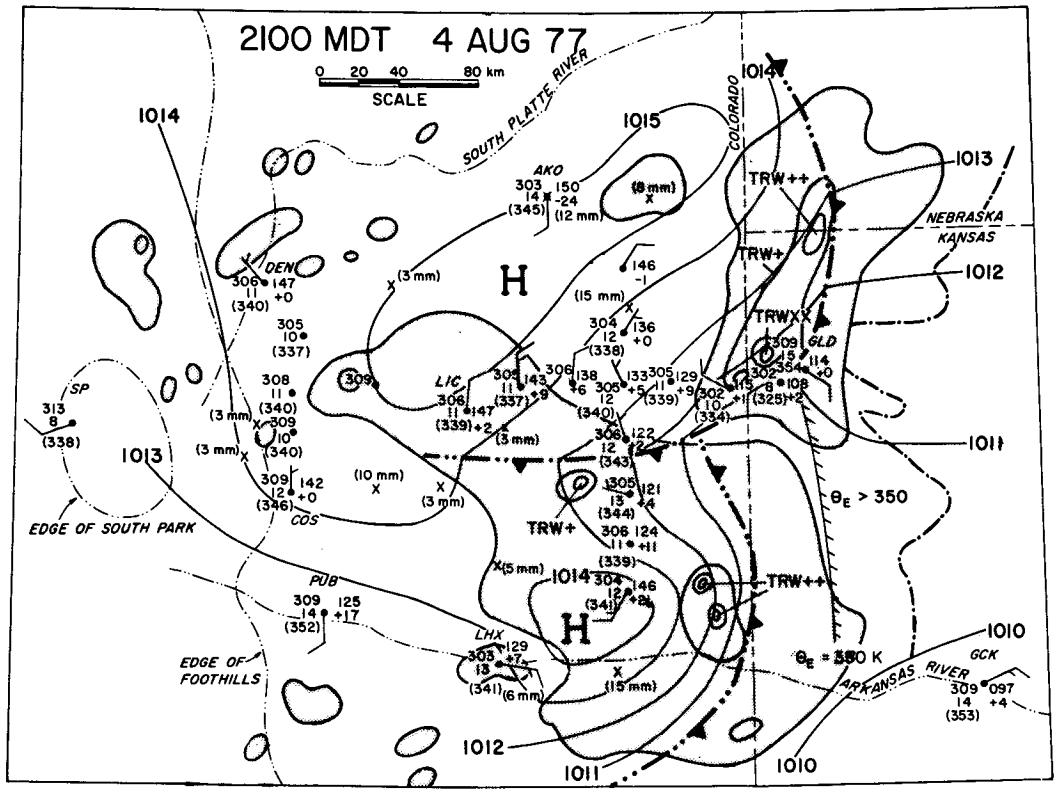

FIG. 31. As in Fig. 26, except 2100 MDT 4 August 1977. Hatched line delineates high θ_e air (>350 K) to the east of the storm. Precipitation values are 3 h accumulations ending at map time (since Fig. 29).

agating line of thunderstorms. With surface precipitation being as light as it was in this and many similar cases, however, one cannot rule out the possibility that other mechanisms may have been operating. For example, it is possible that the temporally coherent and spatially contiguous line of mountain thunderstorms initiates a convectively-reinforced, gravity wave mesoscale disturbance, similar in many respects to the wave-CISK theory developed by Yamasaki (1969), Hayashi (1970), Lindzen (1974), Raymond (1975,1976) and Silva Dias (1979).

It is shown in Part II that this mountain-generated line of convection is only one of several participants in the formation of an MCC. In Part II, the genesis of the mature MCC is examined as its component cumulonimbus clusters propagated through the moist low-level air over Kansas. The structure and dynamic influence of the mature system and finally, its further eastward migration are then explored.

Acknowledgments. Special thanks go to Robert M. Banta for many fruitful discussions, as well as his assistance in data procurement. Additional advice and assistance were provided by Kelvin Danielson, Kevin Knupp, Gregory Tripoli, Prof. Lewis Grant and Dale Grit. Thanks are especially given to Brenda Thompson for processing the manuscript and to Lucy McCall and Bonnie Tripoli for drafting the many complex figures.

Assistance in data gathering and archiving was provided by numerous personnel of the Bureau of Reclamation of the U.S. Department of the Interior, as well as the Field Observing Facility, National Center for Atmospheric Research. This research was supported by the National Science Foundation under Grants ATM-7683361, ATM-7908297 and ATM-8113082, by the U.S. Bureau of Reclamation, Division of Atmospheric Water Resources under Contract 7-07-B0006, and by the National Aeronautics and Space Administration under Grant NSG-0511. Some data processing was performed on the NCAR PAM system and the NCAR CDC-7600. The National Center for Atmospheric Research is supported by the National Science Foundation.

APPENDIX

Objective Analysis Technique for Upper-Air and Surface Observations

The objective analysis technique applied to both upper-level and surface observations was described by Barnes (1973). For upper levels, analyses were on a 2° × 2° latitude/longitude grid from 91 to 123°W and 30 to 50°N. "Observations" utilized include those from the basic U.S., Canadian and Mexican rawinsonde network within and around the analysis domain, supplementary rawinsondes as described in Section 2, and National Meteorological Center 2.5° × 2.5° latitude/longitude grid-point data (Jenne, 1975) in the data-

sparse regions off the west coast and near the southern perimeter of the analysis domain. Weighting parameters were chosen such that observed features with wavelengths of 890 and 1220 km were theoretically reproduced in the objective analyses with responses of 75 and 90%, respectively. The scalar fields of height, temperature, mixing ratio, and u and v wind components were analyzed for the 85, 70, 50 and 30 kPa levels at 1200 GMT 4 August and 0000 GMT 5 August 1977. For stations above 85 kPa (generally within the 1500 m elevation contour in Fig. 9b), reduced 85 kPa heights and surface temperatures, mixing ratios and winds were utilized in the 85 kPa objective analyses. Kinematic and advection fields were computed with centered finite differences (one-sided differencing along the border of the domain). A subjective assessment of the analysis technique can be made by comparing the gridded 50 kPa winds and heights in Fig. 8a with the observed winds in the same figure (which show most of the observation locations) and the manual height analysis in Fig. 3.

Objective surface analyses were conducted for 3 h intervals, on a 1° × 1° latitude/longitude grid, from 93 to 105°W and 33 to 45°N. Weighting parameters were chosen to theoretically reproduce observed wavelengths of 330 and 460 km with 75 and 90% responses, respectively. The western boundary was limited to 105°W, the approximate eastern edge of the Colorado Rockies; carrying the analysis further west would require the use of interior mountain observations, which are not likely to be representative of large-scale fields. All surface observations available from the Bureau of Reclamation data files were utilized (locations shown by station winds in Fig. 22), except for several stations within "weighting distance" of 105°W in Colorado and New Mexico. These were omitted because of their location to the west of major mountain ranges. Their omission does not seriously affect the analyses. Sea-level pressure, altimeter, temperature, dew point, and u and v wind components were gridded from the observations, with the additional thermodynamic variables of station pressure, q, θ and θ_e computed directly from the objectively analyzed fields. A comparison of the objectively analyzed wind and pressure fields in Fig. 22 can be made with the observed winds in the same figure and the manual pressure analysis in Fig. 5e. Kinematic and advection fields were computed as with the upper-air analyses.

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