Evolution of Mesoscale Convective Systems over Mountainous Terrain

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ABSTRACT OF THESIS

EVOLUTION OF MESOSCALE CONVECTIVE SYSTEMS

OVER MOUNTAINOUS TERRAIN

Two detailed, multi-sensor case studies of mesoscale convective storms occurring in summer over the central and eastern Colorado Rockies are presented. These case studies use data taken during the 1977 South Park Area Cumulus Experiment (SPACE) from surface meteorological stations, rawinsondes and tethered balloons, conventional and Doppler radars, powered aircraft, and satellites. The case studies are compared with previous observations and theories relating to diurnal patterns of convective storm activity, especially those relating to thermal forcing of the boundary layer by the daily cycle of solar heating on elevated terrain.

On one case study day, 19 July, 1977, a north-south oriented line of intense convective cells formed and remained within South Park, an elevated plain located within the Rocky Mountains, 2.8 km above sea level. Elevated surface heating in South Park created a region of low-level convergence which imported Pacific moisture from west of the Rockies into South Park. The mesoscale thunderstorm line formed over this convergence zone. Northerly surface flow, having the appearance of a "density current", penetrated into South Park late in the afternoon, enhancing the intensity of convective storms. Cases of cell merger, storm splitting, and various interactions of the storm system with the mesoscale environment were observed. A single large convective cell was then observed to grow on the southern end of the mesoscale line, exhibiting supercell characteristics and substantial modification of the environmental flow.

The case study of 4 August, 1977, documented the creation of mesoscale convective storms in the mountains and their subsequent eastward propagation across the High Plains. Morning upslope winds created cool advection which stabilized the atmosphere over South Park, inhibiting boundary layer growth and suppressing cumulus cloud development. At the same time, high level heating on the higher peaks of the Rocky Mountains created buoyant air parcels which rose convectively to saturation, forming the earliest cumulus clouds. In the early afternoon, convective precipitation echoes began to move eastward by a process of discrete propagation on the east, or downshear side. These storms grew to intense levels as they moved onto the High Plains. Convective activity in the plains was completely suppressed, a process partially attributed to diurnal thermally induced boundary-layer flow patterns, until the passage of the mesoscale squall line released the pent-up convective instability. This squall line maintained its linear shape and rapid propagation speed while exhibiting both extremely severe and nonsevere convective intensity, the variations in intensity being caused by variations in low-level moisture on the High Plains. The timing of convective rainfall from these storms agreed well with climatological data which show the time of maximum rainfall becoming later as one moves farther east. The mesoscale convective storms observed on 4 August, 1977 formed a large nocturnal precipitation area in the central plains. The observations suggest that convective organization results from large-mesoscale thermal terrain effects, combined with mesoscale squall-line dynamics related to meso-high pressure center formation.

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TABLE OF CONTENTS

Section	Page
ABSTRACT OF THESIS	ii
ACKNOWLEDGMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	vii

Chapter		Page
1.0	INTRODUCTION	1
1.1	Statement of the Problem	1
1.2	South Park Area Cumulus Experiment	3
2.0	BACKGROUND	9
2.1	Slope Winds and Mountain-Valley Winds	10
2.2	Evolution of the Subcloud Planetary Boundary Layer	13
2.3	Mountain Thunderstorm Formation, Movement, and Propagation	15
2.4	Significance of Topographic Influences on High Plains Convective Activity	20
3.0	19 JULY 1977 CASE STUDY	37
3.1	19 July 1977 - Synoptic Situation	38
3.2	19 July 1977 - Mesoscale Sounding Data at 1200 GMT	42
3.3	19 July 1977 - Evolution of the Morning Planetary Boundary Layer (PBL)	46
3.4	19 July 1977- Early Afternoon Mountain Thunderstorms	50
3.5	19 July 1977 - Late Afternoon Mesoscale Thunderstorm Line	56
3.6	19 July 1977 - 1800 MDT Larger-Scale Observations	66
3.7	19 July 1977 - Evening Post-Frontal Thunderstorm Activity	73
3.8	19 July 1977 - Summary	87

TABLE OF CONTENTS (Cont'd)

Chapter		Page
4.0	4 August 1977 CASE STUDY - AN EASTWARD PROPAGATING MESOSCALE SYSTEM	90
4.1	4 August 1977 - Synoptic Situation	91
4.2	4 August 1977 - Evolution of the Planetary Boundary Layer	97
4.3	4 August 1977 - Large-Mesoscale Cloud Environment	113
4.4	4 August 1977 - Formation and Propagation of Early Mountain Thunderstorms	119
4.5	4 August 1977 - Evolution of the Intense High Plains Mesoscale Storm	129
4.6	4 August 1977 - Summary	141
5.0	SUMMARY AND CONCLUSIONS	146
5.1	Conceptual Model of Eastward Propagating Orogenic Mesoscale Systems	147
5.2	Significant Results of Case Studies	150
5.3	Suggestions for Future Analysis of SPACE Data	154
5.4	Suggestions for Future Field Programs	157
BIBLIOGRAPHY		158

LIST OF FIGURES

Figure No.	Description	Page
1	Map of terrain in South Park, Colorado. Regions below 9000 ft. (2744m) are hatched; regions above 10,000 ft. (3049m) are lightly shaded, and regions above 12,000 ft. (3659m) are heavily shaded. PAM remote stations are indicated with dark circles accompanied by the station number, with a star for the base site. CP-3 and CBS-4 radars are indicated with dark triangles.	4
2	Map of extended SPACE/HIPLEX experimental area, with averaged terrain contours every 304.8m (1000 ft.). The large circles represent radar effective coverage areas.	7
3	Schematic of the interactions between valley winds and slope winds for a complete 24 hour diurnal cycle. From Defant (1951).	11
4	a) Observed interaction of valley and slope winds near local noon. Similar to Fig. 3c. b) Observed downslope drainage winds before sunrise. Similar to Fig. 3g or 3h. From Buettner (1967).	12
5	Colorado map showing normal May-September precipitation (1931-1960) east of longitude 106^{o}W. Isolines are in inches (1 in. = 25.4mm). From Dirks (1969). Analysis from U.S. Department of Commerce map.	21
6	a) Six groups of stations with north-south orientations used in the timing analysis of convective shower activity. b) Timing of major convective activity for ten-year summary of hourly precipitation $\geq$ .10 inch for the six groups of stations (from Crow, 1969).	25
7	Percentage of summer thunderstorm occurrences per quarter day. From Hydrometeorological Report, 1947.	26
8	a) The mean maximum mixing depth (m) for July, from 10 years sounding data over the contiguous United States. b) Differences, in meters, between mean lifted condensation level and mean maximum mixing depth for July. A positive value (dashed contours) indicates that the condensation level is higher than the mixing depth. (From Holzworth, 1964).	27

9 Change in divergence between two successive sets of balloon wind observations, for all days in August 1947 and August 1948. a) 2200-0400 CST (Central Standard Time; same as MDT, or Mountain Daylight Time) or nighttime. b) 0400-1000 CST, early morning. c) 1000-1600 CST, midday. d) 1600-2200 CST, evening. Levels are 1.2km (4000 ft.), 3.0km (10,000 ft.) and 5.5km (18,000 ft.). From Bleeker and Andre (1951). 29

10 Westerly component of the mean departure vector as a function of altitude and time, derived from 4 x daily balloon flights. Data for 28 undisturbed summer days at Denver, Colorado; Amarillo, Texas; and Dodge City, Kansas. From Dirks (1969). 30

11 Number of low-level wind maxima, here defined as a wind speed of over 12 ms^{-1} occurring below 1.5 km AGL, with a decrease of wind speed above the maximum of 6 ms^{-1} or more, during two complete years, for soundings at 0600 MDT and 1800 MDT. (A total of 1462 soundings at each stations). From Bonner (1968). 34

12 Location of core of the horizontal low-level jet, for 28 selected cases. The star represents the median location of all the jet cores. The envelope contains 26 of the 28 jet axes. Terrain contours in km are included. From Bonner (1968). 34

13 500 mb analysis for 0600 MDT (1200 GMT), 19 July, 1977. Areas with a dew-point depression ($T-T_d$) less than 7°C are marked. Stations used in cross-sections are connected with a bold line. 39

14 Mesoscale surface analysis for 0600 MDT, 19 July, 1977. Temperature and dew-point in Deg. C. Note pressure trough in eastern Colorado. 40

15 Infrared (IR) Satellite image of western U.S., 0600 MDT, 19 July, 1977. Dotted lines are state boundaries. Various shades represent different IR temperatures according to the succession drawn at the top of the figure (temperature decreasing toward the right). Thus, large cold cloud tops representing intense convective cells appear as black or black-outlined areas within the white mass of lower clouds. 41

16 South Park sounding for 0600 MDT (1200 GMT), plotted on skew-T, log-P diagram. 43

FIGURES (con't) Page

17	East-west cross-section including soundings from Grand Junction (GJT), South Park (SP), and Limon (LI), Colorado and Goodland (GL), Kansas. Solid contours are potential temperature (°K) and dashed contours are water vapor mixing ratio (gm kg^{-1}). Terrain elevations and stable layer boundaries are marked with bold lines. Valid for 0600 MDT, 19 July, 1977.	45
18	PAM surface data taken in South Park. a) at 0600 MDT, b) at 0800 MDT and c) at 1000 MDT, 19 July, 1977. Five-minute averaged potential temperature (°K), water vapor mixing ratio (gm kg^{-1}) and winds are plotted at each station. DM means data missing for that time.	47
19	South Park sounding of 1000 MDT, 19 July, 1977, plotted on skew-T log-P diagram.	49
20	South Park sounding of 1246 MDT, 19 July, 1977, plotted on skew-T log-P diagram.	51
21	Composite PAM-CP-3 radar plot for 1239 MDT, 19 July, 1977. Surface data as in Fig. 18. Radar contours are 5.5° constant elevation scans, projected onto a horizontal surface. olid contours are 25 dBz, dashed contours are 40 dBz. Key to other symbols is given above.	52
22	Same as Fig. 21, for 1333 MDT.	55
23	Same as Fig. 21, for 1452 MDT.	57
24	Same as Fig. 21, 1623 MDT. Individual convective cells are labeled C1, C2, etc. Averaged speed and direction of the reflectivity core of certain selected cells are tabulated in the lower left corner.	59
25	Same as Fig. 24, for 1638 MDT.	61
26	Same as Fig. 24, for 1702 MDT.	62
27	Same as Fig. 24, 1720 MDT.	64
28	Same as Fig. 24, for 1742 MDT.	65
29	Same as Fig. 13, for 1800 MDT, 19 July, 1977 (0000 GMT, 20 July, 1977).	66
30	Same as Fig. 15, for 1800 MDT, 19 July, 1977.	68

FIGURES (con'd)

		Page
31	Limon radar summary for 1930 MDT, 19 July, 1977. Dark contours are radar echoes, with contour levels as in Table 1. Concentric circles are range from Limon in 46 km increments.	69
32	Mesoscale surface map, like Fig. 14, for 1800 MDT, 19 July, 1977.	70
33	South Park sounding of 1710 MDT, 19 July, 1977, plotted on skew-T log-P diagram. Winds between the surface (720 mb) and 500 mb are estimated.	74
34	Same as Fig. 24, for 1758 MDT.	76
35	Same as Fig. 24, for 1822 MDT.	78
36	Same as Fig. 24, for 1844 MDT.	80
37	Same as Fig. 24, for 1856 MDT.	82
38	Same as Fig. 24, for 1922 MDT.	83
39	Same as Fig. 24, for 1939 MDT.	85
40	Total rainfall in mm observed at PAM stations, for the time period 1600-2400 MDT, 19 July, 1977. Contour interval 5 mm.	86
41	Upper air analyses as in Fig. 13, for a) 500 mb and b) 700 mb levels, 0600 MDT, 04 August, 1977.	92
42	Extended area surface analysis, similar to Fig. 14, for 0600 MDT, 04 August 1977.	93
43	Satellite infrared (IR) image of western U.S., similar to Fig. 15, for 0400 MDT, 04 August 1977. The huge mesoscale convective storm in the central plains is descended from storm systems which formed in eastern Colorado the previous day, (03 August 1977).	95
44	East-west cross-section, as in Fig. 21, for 0600 MDT, 04 August 1977.	96
45	South Park sounding of 0551 MDT, 04 August 1977, plotted on skew-T log-P diagram.	99
46	PAM surface data from South Park, as in Fig. 18, for a) 0600 MDT and b) 0700 MDT, 04 August 1977.	100

FIGURES (cont'd)

		Page
47	Boundary Layer Profiles (PBL) tethered balloon soundings. Potential temperature, water vapor mixing ratio, and winds plotted against height in meters AGL. Soundings begun at a) 0619 MDT, and b) 0649 MDT, 04 August 1977, both at Site #2.	101
48	Same as Fig. 47, for a) 0720 MDT, Site #2, and b) 0836 MDT, Site #1, (CSU base site).	103
49	Same as Fig. 46, for a) 0800 MDT, and b) 0900 MDT, 04 August 1977 (water vapor mixing ratio data missing for 0900 MDT). Dashed line encloses region with mixing ratio >6.5 gm kg^{-1}.	105
50	Plot of potential temperature and dew-point vs. time, at the CSU base, 0600-1300 MDT, 04 August 1977.	105
51	Same as Fig. 46, for a) 1000 MDT, and b) 1100 MDT, 04 August 1977.	106
52	South Park sounding of 1030 MDT, 04 August 1977, plotted on skew-T log-P diagram.	108
53	Same as Fig. 47, for a) 1054 MDT, and b) 1218 MDT, taken at Site #1 (CSU base).	109
54	Temperature, dew-point, and wind speed plotted vs. time, at PAM station #6 (Horseshoe Peak), for 0600-1300 MDT, 04 August 1977.	110
55	South Park sounding of 1301 MDT, 04 August 1977, plotted on skew-T log-P diagram. Cloud Condensation Level (CCL) marked.	114
56	East-west cross-section, as in Fig. 17, for 1200-1300 MDT, 04 August 1977. Average winds in the PBL, along with PBL depth, are plotted for 4 stations (SP, LI, GL, and Denver) in the lower margin. Data from a west-to-east aircraft flight are included in analysis.	115
57	Surface map using SPACE/HIPLEX mesonet data on the High Plains. Surface pressure and surface water vapor mixing ratio are contoured. Limon radar outline and station key are provided.	116

FIGURES (cont'd)

		Page
58	Visible satellite images, processed by video imaging techniques showing eastern 2/3 of Colorado and part of New Mexico. State borders in Fig. a) Town of Fairplay, about 10 km north of CSU base, is labeled. The town is located at the lower left corner of the label. The dark surface feature, lower right of each figure, is the Arkansas River east of Pueblo. The Palmer Lake Divide is marked by clouds, just north of the Arkansas River, especially in Fig. 58b. Picture times are a) 1200 MDT, b) 1245 MDT, c) 1315 MDT, d) 1345 MDT, e) 1415 MDT, and f) 1442 MDT.	121
59	Composite radar summaries from the region between Fairplay (FP) and Limon (LIC), using data from CP-3, CBS-4, and Limon NWS radars. Intensities in dBz, echo tops are in km MSL. Cells referred to in text are labeled. Summary times are a) 1245 MDT, b) 1315 MDT, c) 1347 MDT, d) 1416 MDT, and e) 1444 MDT.	122
60	PAM-CP-3 summary, as in Fig. 24, for 1254 MDT, 04 August 1977.	123
61	CP-3 radar countour data, on same scale as Fig. 24, and other PAM-CP-3 figures for 1316 MDT, 04 August 1977. Outer bold contour level is 25 dBz, inner bold contour is 40 dBz. (PAM data not available at this time).	125
62	Same as Fig. 60, for 1336 MDT.	127
63	Same as Fig. 60, for 1413 MDT.	128
64	SPACE/HIPLEX surface map, similar to Fig. 57 with mixing ratio contours omitted, for 1500 MDT, 04 August 1977. Thunderstorm intensity designations as in Table 1.	130
65	Satellite images of western U.S., on 04 August 1977, for a) 1530 MDT (visible image), b) 2230 MDT (visible), c) 1800 MDT (visible), d) 2100 MDT (infrared image), e) 2230 MDT (IR), and 0500 MDT, 05 August 1977 (IR).	132
66	Similar to Fig. 64, for 1700 MDT, 04 August 1977. Bold dashed line is edge of Goodland radar echo.	133
67	Limon sounding for 1705 MDT, 04 August 1977, plotted on skew-T log-P diagram.	135
68	Same as Fig. 56, for 1700-1800 MDT, 04 August 1977. Aircraft flew east to west.	137

FIGURES (cont'd) Page

69	Same as Fig. 66, for 1800 MDT, 04 August 1977.	139
70	Same as Fig. 66, for 2100 MDT, 04 August 1977.	142

1.0 INTRODUCTION

The purpose of this investigation is to determine the influences of mountainous terrain on observed patterns of summertime cumulus and cumulonimbus activity. Specifically, it is desired to understand more fully the summertime diurnal pattern of convective activity over the mountains and plains of central and eastern Colorado. To accomplish this objective, data taken in the summer of 1977 during the comprehensive Colorado State University (CSU) South Park Area Cumulus Experiment (SPACE) are examined in detail.

1.1 Statement of the Problem

It has long been observed in mountainous regions that summertime cumulus clouds form earliest in the day over the slopes of high mountain peaks and ranges. Precipitation data show that mountain ranges receive more rainfall in the summer than nearby valleys and plains. In Colorado (latitude 37^{o}-41^{o}N), summertime precipitation shows a minimum on the western edge of the Great Plains (elev. 1.5 km), 50-100 km east of the high ridge of the Front Range and Sangre de Cristo mountains (elev. 3.0-4.2 km) (Dirks, 1969). Radar data (Henz, 1974) indicate that precipitating cells tend to form preferentially over certain east-facing slopes of the Front Range ("hot spots"), and that much of the precipitation which does fall in the plains immediately east of the Front Range comes from convective cells which form over the "hot spots" and then move eastward over the plains. Thus, a large, populated agricultural area is partially dependent on a much smaller genesis region for vital summertime precipitation.

On a larger scale, summertime precipitation gradually increases as one travels farther east from near the Rockies. The high plains of Eastern Colorado and Western Kansas depend for most of their precipitation on traveling mesoscale convective systems, which often take the form of squall lines (Brunk, 1953). Precipitation and thunderstorm activity occur progressively later in the day, on the average, as one moves eastward (Crow, 1969; Wallace, 1975). In the central U.S. (Iowa, eastern Kansas and western Nebraska), the daily precipitation maximum occurs just before sunrise, completely out of phase with the diurnal solar heating cycle. Many of the physical mechanisms which have been proposed to explain this progression are based on the presence of the Rocky Mountain barrier to the west and on the gradual slope of the plains toward the Rockies.

By utilizing two case study days from the SPACE 1977 data set, the processes by which the topography of central and eastern Colorado influences the various scales of convective activity are described in this thesis. Surface and sounding data are used to document the morning evolution of the planetary boundary layer, up to the stage at which cumulus clouds develop over the mountain peaks. Radar, aircraft, satellite, and surface data show the growth of thunderstorms over the mountains and their patterns of new growth, translation, and propagation. Finally, surface data, radar, satellite, soundings, and aircraft document one of the days on which mesoscale convective systems formed at the edge of the mountains and moved eastward across the plains, evntually evolving and merging into a large nocturnal heavily-precipitating mesoscale system over the central plains.

1.2 South Park Area Cumulus Experiment

The South Park Area Cumulus Experiment (SPACE) of Colorado State University (CSU) is a comprehensive summertime meteorological program. The field portion of the program is located in South Park, Colorado, a broad elevated (2.6-3.2 km MSL) valley about 120 km southwest of Denver (Fig. 1). The edge of the plains to the north and south drops to about 1.6 km, but the Palmer Lake Divide, a broad, partially wooded ridge, extends another 80-100 km eastward, with elevations of up to 2.1 km MSL.

The western edge of South Park, on the slopes of the Mosquito Range, has long been recognized as a genesis region for cumulus and cumulonimbus clouds. CSU has previously conducted field programs in this area in 1973, 1974, and 1975. The emphasis in these programs was on cloud microphysics and precipitation processes (see Danielson, 1975 and Huggins, 1975). Instruments used included rawinsondes, surface weather stations, stereo cloud cameras, raindrop disdrometers, a hail chase vehicle, 10 cm search radar, CHILL pulsed doppler radar, powered aircraft, and the National Center for Atmospheric Research (NCAR) sailplane. Much of the success of these programs was due to their ideal location. Cumulus and cumulonimbus clouds form with great regularity within a relatively small area. The time of first cumulus cloud and first radar echo formation can be closely estimated using rawinsonde and surface data.

For 1977, the scope of the SPACE was expanded. Attention was focused on the role of the mountains and South Park in influencing the mesoscale precipitation patterns of the plains and Palmer Lake Divide

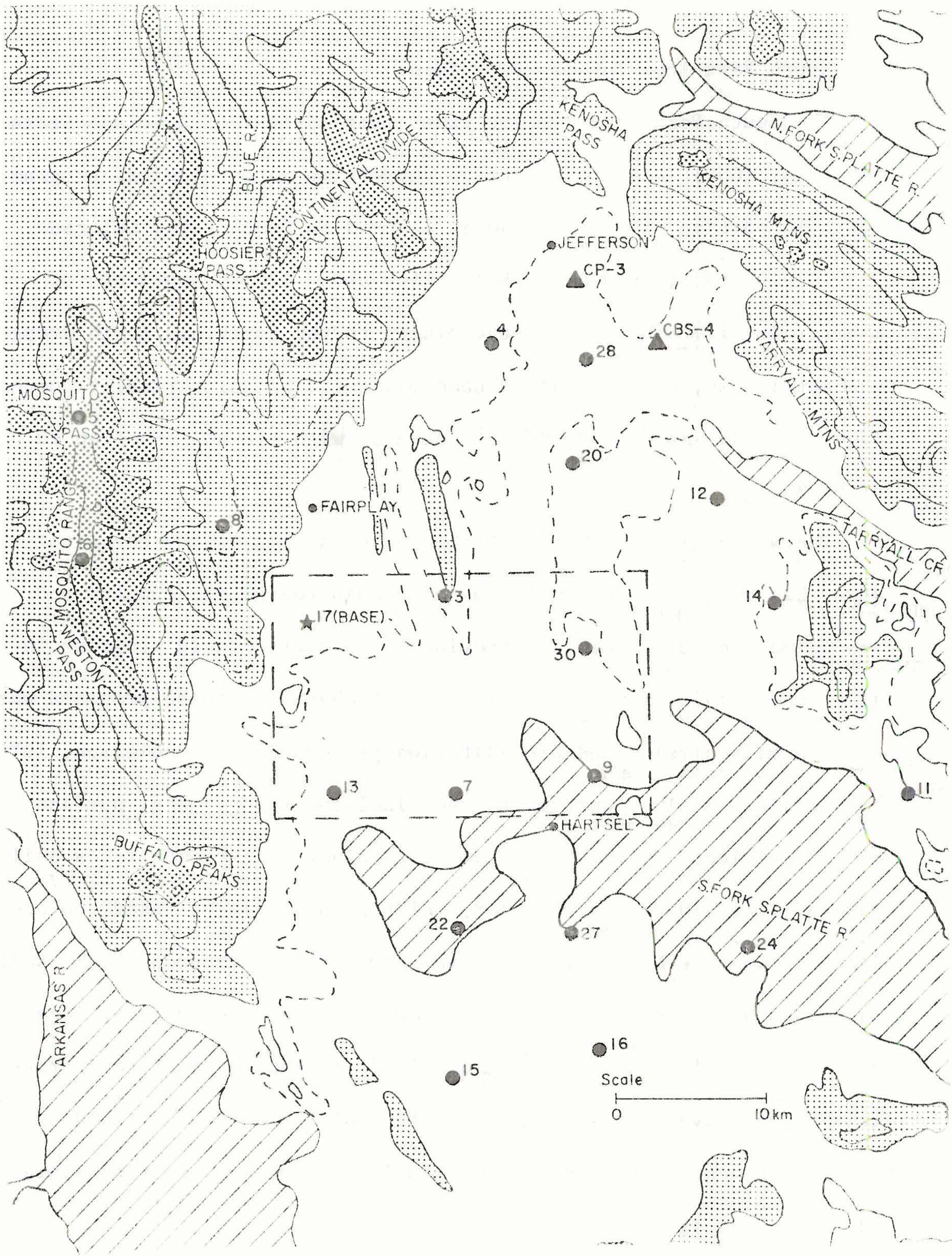


Figure 1. Map of terrain in South Park, Colorado. Regions below 9000 ft. (2744m) are hatched; regions above 10,000 ft. (3049m) are lightly shaded, and regions above 12,000 ft. (3659m) are heavily shaded. PAM remote stations are indicated with dark circles accompanied by the station number, with a star for the base site. CP-3 and CBS-4 radars are indicated with dark triangles.

to the east. The various types of field equipment were deployed on several different spatial scales.

The South Park scale (Fig. 1) 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 UVW anemometers (which measure three orthogonal components of the wind) and thermistors, (which measure air temperature) at various levels on two towers, two Boundary Layer Profiler (BLP) tether balloons, and a Doppler acoustic sounder. Rawinsondes were launched from the CSU base daily at 1200 GMT (Greenwich Mean Time), or 0600 MDT (Mountain Daylight Time, which is 6 hours earlier than GMT), 1600 GMT (1000 MDT), and 1900 GMT (1300 MDT). On selected days of interest, rawinsondes were also launched at 2300 GMT (1700 MDT) and 0300 GMT (2100 MDT). The base was also the site of the National Oceanic and Atmospheric Administration (NOAA) Lidar system, which included a 1 cm radar and a large array of radiation sensors as well as the Lidar equipment (see Danielson and Cotton, ed., 1977).

The National Center for Atmospheric Research (NCAR) Portable Automated Mesonet (PAM) was deployed on the South Park scale (Cotton and George, 1978). Twenty remote weather stations were spaced roughly on a 10 x 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 m above the ground, wet- and dry-bulb temperatures and pressure from 2 m above the ground, and rainfall in .24 mm increments with a tipping bucket rain gauge. The

PAM base van was located at the SPACE base. The data were obtained from the remote stations by radio telemetry once per minute, and were instantly available for display by a computer graphics terminal located in the base van.

Triple Doppler radar data were also taken on the South Park scale. NOAA provided two 3.2 cm wavelength (X-band) Doppler radars, and NCAR provided the 5.5 cm (C-band) 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. During the period July 10-August 1, the CP-3 radar also provided full volume (360°) scans in addition to coordinate sector scans. CP-3 was chosen for this task because it provides more reliable reflectivity data than the NOAA radars, and because its scan rate is faster than the NOAA radars', allowing it more free time during the triple-Doppler experiments to perform full volume scans. After August 1, 1977, the 10 cm CSU FPS-18 radar (CBS-4) was available to perform full volume scans. This radar was located on higher ground about 7 km southeast of CP-3, where it had a much better view toward the east.

Aircraft measurements were also concentrated on the South Park scale. The twin-engined NCAR Queenair (304D), equipped with a gust probe as well as basic meteorological instruments, flew "butterfly" patterns at several different levels. The flight legs covered an area about 33 x 37 km, cenetered on the SPACE base, and were flown mostly in the mornings during July 1977. The NOAA/NCAR cloud physics sailplane flew cloud penetrations in South Park during both July and August, often in coordination with the Lidar system and Doppler radar. The sailplane was also coordinated with the two Bureau of Reclamation cloud physics aircraft, which flew cloud penetration, first echo studies, and small-mesoscale (South Park scale) patterns during August.

In conjunction with the Bureau of Reclamation 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. 2). Three rawinsondes were launched daily from Limon, Colorado, usually at 0600 MDT (1200 GMT), 1300 MDT (1900 GMT), and 1800 MDT (0000 GMT). Two or three rawinsondes were launched daily by HIPLEX personnel at Goodland, Kansas, usually at 0600 MDT (some days), 1200 MDT, and 1800 MDT. These were supplemented by regular National Weather Service (NWS) soundings

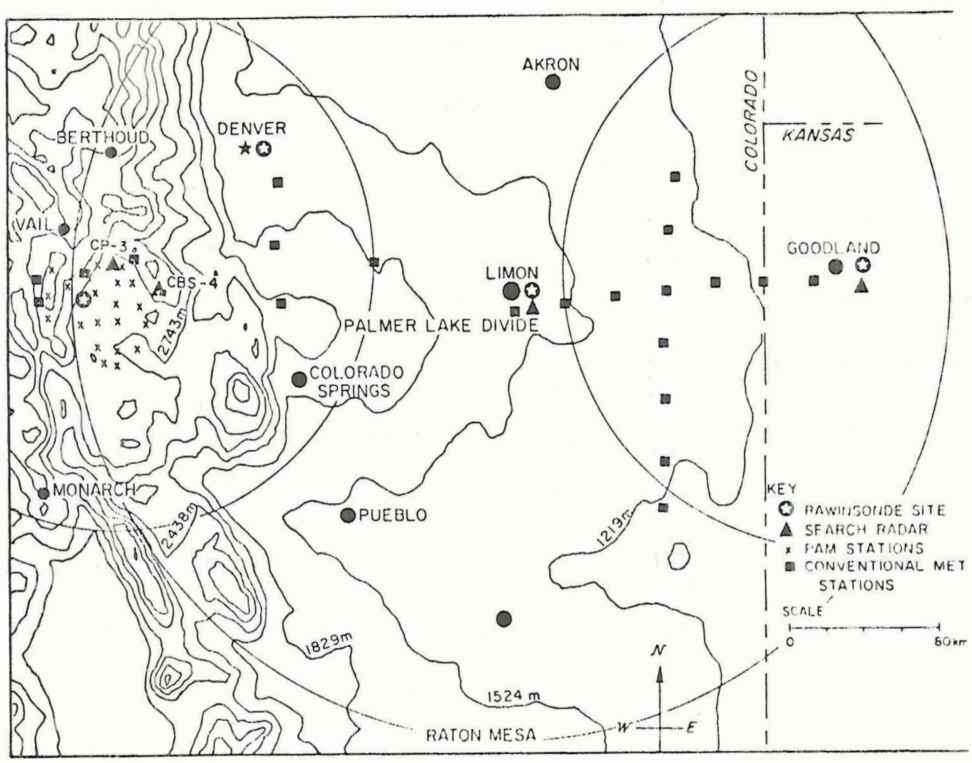


Figure 2. Map of extended SPACE/HIPLEX experimental area, with averaged terrain contours every 304.8m (1000 feet). The large circles represent radar effective coverage areas.

at 0600 MDT and 1800 MDT, 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 are also available from the NWS WSR-57 radar at Limon (PPI photos and traces only) and the HIPLEX radar at Goodland. These three radars generally provided continuous coverage of eastward moving storms from the central Rockies to western Kansas. Satellite data applicable to this larger scale are available in visible and infrared, with several days' data having been digitized and stored on magnetic tape. Two days of "rapid scan" satellite imagery are available, taken at three or nine minute intervals. Also on "rapid scan" days, supplementary rawinsondes were taken at 1200 MDT at five NWS rawinsonde sites, including Denver and Grand Junction, Colorado.

In the two case study analyses, most of these data sources have been utilized. Soundings and vertical cross sections have been constructed using Grand Junction, South Park, Limon, and Goodland rawinsondes, tether balloons, and powered aircraft. Surface maps have been constructed using PAM and conventional surface data, composited with CP-3 radar data. Radar summaries using CBS-4, CP-3, Limon, and Goodland radars are used on a larger scale, also composited with surface data, and compared with satellite cloud pictures. As each data type is introduced, the analysis technique is decribed in greater detail.

2.0 BACKGROUND

The effects of mountainous terrain on the formation of cumulus clouds and cumulonimbus systems can be divided into two basic classes. One class consists of purely dynamic effects resulting from deflection or alteration of a pre-existing mean flow by terrain features. Examples of this class are orographic cloud formation and genesis of cyclonic storms in eastern Colorado, on the lee side of the mountains relative to the prevailing westerlies. This class dominates precipitation patterns in the winter, and during passage of synoptic storms.

The second class of terrain effects includes dynamic and thermodynamic effects resulting from the diurnal cycle of solar heating on the mountainous terrain. Heating and cooling of the air near the slope surface creates horizontal temperature and pressure gradients, relative to the free air at the same elevation. These pressure and temperature gradients drive various types of flow patterns, including slope winds, mountain-valley winds, katabatic outflow, etc. Surface heating at high elevations creates a very deep planetary boundary layer (PBL) and increases the instability of the atmosphere. The combination of a deep PBL, enhanced instability, and upslope winds can create ideal conditions for the formation and growth of cumulus clouds and cumulonimbus systems. This class of motion is most important in the summer, and when synoptic scale forcing is weak.

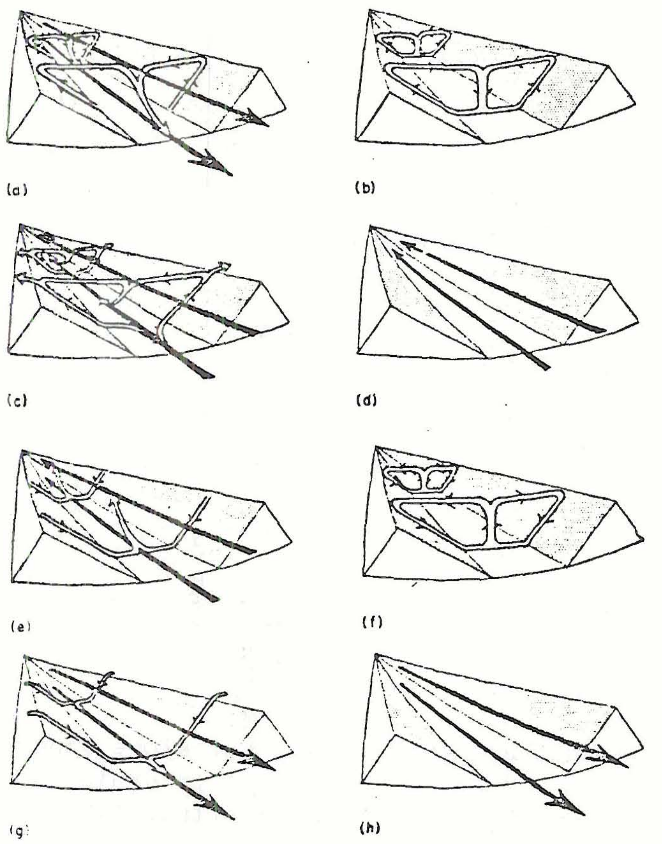
This chapter consists of a review of observations and theories by various researchers which relate to thermally induced flow patterns around mountainous terrain, and the convective storm systems which are influenced by these patterns. Special attention will be focused on the Colorado Rockies and the Great Plains to the east.

2.1 Slope Winds and Mountain-Valley Winds

Local upslope winds on mountain slopes have been noticed for centuries, and have been written about in the literature since 1840 (see Dirks, 1969). Detailed aerological studies of slope and valley winds were made in the Alps in the 1930s. A review of these studies by Defant (1951) summarized the earlier slope wind observations and theories.

Basically, upslope winds are caused by heating of the air next to the slope, so that it is warmer and less dense than the adjacent free air at the same elevation. On a mountain slope, upslope winds commence 1/4 to 3/4 hours after sunrise, and continue until sunset (Defant, 1951). The depth of upslope flow is typically 100-200 m, with speeds about 3-5 ms^{-1}. At sunset, the surface wind quickly shifts to a downslope direction through a somewhat shallower layer.

On a larger scale, diurnal winds also blow up and down mountain valleys. The distinction here made between valley winds and slope winds is that valley winds occur on horizontal scales larger than any individual slope. Hence, valley winds do not necessarily blow in a direction parallel to the local terrain fall line, as do slope winds. Defant (1951) reported results of the Alpine valley wind observations by A. Wagner and others. Wagner observed that the diurnal temperature range is greater in the higher reaches of the valley than below. This creates a surface pressure gradient which drives the valley wind. Fig. 3 (from Defant, 1951) shows how slope winds on the sides of the valley combine with the up-and-down valley component in a complex



Schematic illustration of the normal diurnal variations of the air currents in a valley. (After F. Defant [17].)
(a) Sunrise; onset of upslope winds (white arrows), continuation of mountain wind (black arrows). Valley cold, plains warm.
(b) Forenoon (about 1900); strong slope winds, transition from mountain wind to valley wind. Valley temperature same as plains.
(c) Noon and early afternoon; diminishing slope winds, fully developed valley wind. Valley warmer than plains.
(d) Late afternoon; slope winds have ceased, valley wind continues. Valley continues warmer than plains.
(e) Evening; onset of downslope winds, diminishing valley wind. Valley only slightly warmer than plains.
(f) Early night; well-developed downslope winds, transition from valley wind to mountain wind. Valley and plains at same temperature.
(g) Middle of night; downslope winds continue, mountain wind fully developed. Valley colder than plains.
(h) Late night to morning; downslope winds have ceased, mountain wind fills valley. Valley colder than plains.

Figure 3. Schematic of the interactions between valley winds and slope winds for a complete 24 hour diurnal cycle. From Defant (1951).

manner. Wagner found that the diurnal temperature and pressure variations over the center of the valley were equalized at about the height of the surrounding ridges.

Mountain-valley winds usually begin somewhat after slope winds, according to the size, shape, and aspect of the valley. Both slope and valley winds commence earlier on slopes which face eastward and thus receive enhanced solar heating during the morning hours. Buettner (1967) observed valley winds of over 1 km depth, somewhat deeper than the valley itself (Fig. 4a), with upslope winds on at least one side of the valley (Fig. 4a corresponds to Fig. 3c). Above the valley wind, an anti-valley wind, possibly return flow, exists in a layer about 500 m deep. A similar, but reversed, flow exists at night (Fig. 4b,

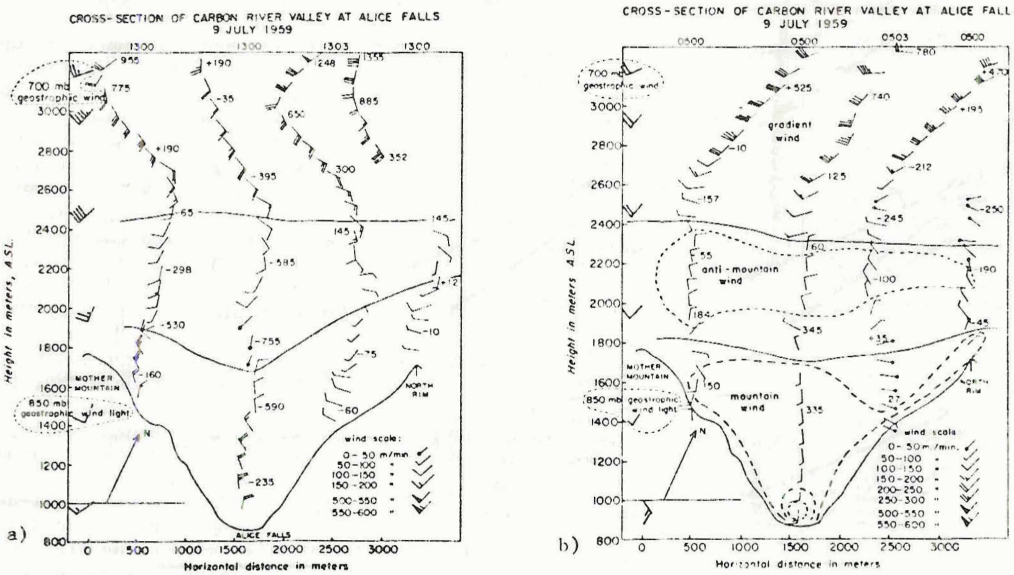


Figure 4. a) Observed interaction of valley and slope winds near local noon. Similar to Fig. 3c. b) Observed downslope drainage winds before sunrise. Similar to Fig. 3g or 3h. From Buettner (1967).

corresponding to Fig. 3g). Above the direct and indirect circulations, the gradient wind prevails.

Many deviations from this idealized valley flow are possible. The Maloja effect, observed both in the Alps (Defant, 1951) and the Cascades (Buettner, 1967) is a reversal of the "normal" valley wind. It is caused by thermal slope winds which occur on a scale larger than that of the valley in question, as might occur if a larger valley lies on the opposite side of a mountain pass. If a valley is too broad, the gradient wind will overcome the valley flow. Whiteman and McKee (1977) observed that in winter, the valley wind can occur <u>above</u> a strong temperature inversion, which lowers to the surface as the day progresses.

2.2 Evolution of the Subcloud Planetary Boundary Layer

We have seen that local slope winds and the more general mountain-valley winds occur in response to thermal differences between mountain slopes and the adjacent free air. This thermal forcing also largely determines the structure of the planetary boundary layer (PBL).

The pattern of PBL evolution over flat terrain is well known (Deardorff, 1967; Tennekes, 1973). Before sunrise, a surface-based inversion exists, typically 300 m deep, above which the vertical lapse rate is almost neutral. After sunrise, surface heating generates a thin neutral layer below the inversion, which slowly grows deeper, as the surface rapidly warms. By mid-morning, the nocturnal inversion is gone, and the neutral PBL is growing rapidly through the marginally stable layer; however, the surface temperature is increasing more slowly. As the PBL depth increases, the depth and strength of the surface superadiabatic layer also increases. At the top of the PBL, buoyant bubbles from the surface layer penetrate above the neutral layer, entraining mid-tropospheric air and causing the PBL to grow. The depth to which the boundary layer grows is limited by mid-tropospheric stability, vertical motion, cloud formation, possible horizontal advection, precipitation downdrafts, etc. Around sunset, the surface inversion re-establishes itself, causing a rapid, large reduction in vertical mixing and shear stress.

Over mountainous terrain, PBL evolution may be far more complex. SPACE 1977 data have already revealed some of these complexities. Before sunrise, the mountain slopes act to cool the surface layer, generating downslope drainage winds, which tend to pool the coldest, most stable air (lowest potential temperature) in local depressions, river valleys, etc. (George and Cotton, 1978). Upvalley winds in South Park form within a thin convective PBL, typically 1-2 hours after sunrise (Banta and Cotton, 1979). The onset of upslope winds is often accompanied by a sudden temperature drop and moisture increase at the surface. Some implications of this cool upslope flow to vertical stability and subsequent PBL evolution were revealed in the course of the case study analysis of August 4, 1977. The data and a more detailed discussion of PBL evolution in South Park are presented in chapters 4 and 5.

Cumulus clouds have long been observed to form earliest over the slopes of high mountain peaks and ridges. Braham and Draginis (1960), using aircraft measurements, observed a wide column of air, somewhat cooler than the environment, over a mountain peak in southern Arizona at the time of first cumulus formation (1000 LST). This air had been lifted about 1.5 km, whereas pre-sunrise measurements showed that the mountain barrier produced only 300 m of orographic lifting, with environmental winds of 3-5 ms^{-1}. Braham and Draginis attributed this enhanced lifting to local convergence over the peaks and ridges caused by slope winds. This mechanism could overcome the negative buoyancy caused by a stably stratified atmosphere and cool advection caused by slope winds. Additional buoyancy would result from a virtual temperature excess caused by moisture advected from low levels by upslope winds.

A competing mechanism for orogenic inducement of cumulus clouds is the idea that large amounts of positive buoyancy would be created by strong heating on the steep mountain slopes. Thus, a series of large, buoyant parcels would be produced near the mountain peaks, and would rise because of buoyant forces. A passing aircraft could sample this parcel after it had overshot the level of neutral buoyancy in a stably stratified environment, giving the appearance that the aircraft had passed through a "cold core" updraft. An early two-dimensional model study of upslope winds (Orville, 1964) indicated that cold core updrafts may be important in an initial environment whose potential temperature increased vertically at 1°K/km, while of course only buoyant parcels are produced in a neutral initial environment. Thus, the updrafts will be more and more buoyant as the day progresses and the environment becomes less stable.

In South Park, the first cumulus clouds appear, usually over the Mosquito Range, at about 0930 MDT or 1000 MDT (sunrise at 0620 MDT). SPACE aircraft data (Banta and Cotton, 1979), indicate that a cold updraft, similar to that found by Braham and Draginis (1960) may be present at about 0900 MDT over the Mosquitoes. Other SPACE data, presented in chapter 4, indicate that surface air parcels are thermally buoyant at the time of first cumulus cloud formation.

2.3 Mountain Thunderstorm Formation, Movement, and Propagation

Convective precipitation (Fujita, 1967) and radar precipitation echoes (Huggins, 1975) also tend to be maximized near the highest mountain peaks, for many of the same reasons that small cumulus clouds form earliest over these peaks. In this section, we will discuss the formation of the first thunderstorms over the mountains and their subsequent patterns of translation and propagation.

The regular occurrence of thunderstorms which are induced by thermal heating on the elevated terrain (which we call "orogenic" thunderstorms) in or near South Park makes it an ideal site for a variety of convective storm research activities. Danielson (1975) used stereo photogrammetry to measure initial cumulus size and subsequent growth during SPACE 1973. Huggins (1975) used an M-33 radar to document initiation and growth of precipitation echoes in the same clouds. Some ideas of the processes which initiate mountain thunderstorms can be gained by comparing their cloud and echo observations with the available South Park rawinsondes.

South Park soundings from 1973 indicate that a strongly stable or inversion layer was present in the layer 500 mb - 400 mb on many convective days, early in the day. Averaged soundings from 12 experimental days (days on which mountain thunderstorms were observed with radar), taken at 0800 MDT and 1130 MDT (Huggins, 1975), indicate the following:

i) The strength and vertical extent of the stable layer <u>decreased</u> between 0800 MDT (before any small cumulus clouds had formed) and 1130 MDT (after formation of orogenic cumulus clouds).

ii) By 1130 MDT, the convective PBL extended up to 550 mb, or about 5.0 km MSL.

iii) Average convective cloud base was also 550 mb, with an area of positive buoyancy (conditional instability) extending to the average inversion level at 460 mb (6.2 km MSL).

Huggins' average first radar echo for the 12 cases in 1973 extended from 505 mb at the echo base to 385 mb, or 7.5 km MSL, at the initial echo top. Thus, the first echo occurred in a convective thermal which penetrated the level of the mean inversion at 460 mb. Average time of the first echoes was 1200 MDT, somewhat after the 1130 MDT rawinsondes, which suggests that cumulus convection was being capped by a weakening inversion at 460 mb on the 1130 MDT soundings. Danielson (1975) presented a case in which the height of small orogenic cumulus clouds grew to 7.0 km MSL before 1000 MDT, then remained constant until 1045 MDT, when one cloud suddenly grew to over 15 km. The 1000 MDT sounding for that day shows a weak stable layer at 410 mb, or 7.0 km.

The pattern of these observations can be explained partly as being a case of clouds modifying the environment. The earliest cumulus clouds would form below the inversion, with cloud top at or just above the inversion, due to the upward momentum of the buoyant cloud parcels. By a process of warming below the inversion through release of latent heat, and cooling above the inversion by evaporation at cloud top, the small cumulus clouds would tend to eliminate the inversion and create a moist adiabatic lapse rate in the cloud layer. Simultaneously, the deep PBL would slowly warm up, further decreasing stability. Thus, the barrier to deep convection would be removed by about 1200 MDT, allowing formation of clouds deep enough, and with cold enough tops, to initiate an ice-phase precipitation process and form precipitation radar echoes.

A radar climatology of first echoes (Huggins, 1975) in the South Park area revealed the presence of preferred mountain thunderstorm genesis areas, or radar "hot spots". Two of the strongest of these are on the east slope of the Ten-mile Range just north of Hoosier Pass and on the eastern foothills of the Mosquito Range a few km northwest of the SPACE base. Using Limon radar data, Henz (1974) showed that first echoes preferred certain areas of the Front Range, particularly east-facing slopes between 2.0 km and 2.3 km MSL. Henz' study did not include the higher ranges of the Rockies or South Park. Median time of earliest echo formation was about 1100 MDT in most of Henz' Front Range "hot spots". This might be slightly earlier than the time of first echo in South Park. Henz concluded that the importance of "hot spots" was associated with their favorable slope, aspect, and access to Plains low-level moisture, which would create moist, convergent upslope winds over the "hot spots". Thus larger, moister cloud parcels than those occurring in South Park might overcome the upper inversion more easily. The significance of "hot spots" to High Plains precipitation patterns will be discussed in a later section.

Once formed, early mountain convective cells (precipitation echoes) tend to move and propagate downwind relative to the mean upper winds, which are usually (but not always) between southwest and northwest. Whether or not these systems can persist and grow as they move away from their genesis region is dependent on a complex set of environmental conditions.

Erbes (1978) studied the motions of echo systems detectable from the Kenosha Pass radar site during the 1974 SPACE field program. He found that those systems which moved a substantial distance downwind did so by means of discrete propagation on their forward edge (downwind and downshear relative to the cloud layer). The right forward flank of the storm system (relative to mean winds) was the preferred location for new cell growth. Cell speed was usually about half of mean wind speed, while system propagation speed sometimes exceeded wind speed. Erbes proposed that this propagation could be explained as occurring in an area of convergence between coherent upslope easterly winds (containing enhanced low-level moisture) and penetrative downdrafts from the already existing cells. These downdrafts would serve to bring westerly momentum from the cloud layer down to the surface. Being cooler than the low-level environment, the downdrafts would flow downhill, also tending to increase their westerly momentum, and thus increase the amount of low-level convergence ahead of the storm system. A major objective of SPACE 1977 was to explore this concept further, using PAM surface stations to locate these "downdraft fronts" in space and time, and radar to detect developing cells. Erbes also noticed that the strength of a propagating system was greater when mean winds were stronger. This could be due partly to stronger convergence resulting from stronger downdraft winds.

Eastward propagating systems such as those examined by Erbes (1978) were the prime focus of the SPACE 1977 field program. In these systems, the direction of the upper winds, vertical wind shear, thunderstorm downdrafts, cell translation, and system propagation are all basically westerly. Thus, individual cell downdrafts act to increase convergence ahead of the cell and directly promote system propagation. However, the case study analysis of July 19, 1977 (chapter 3) has revealed that another type of storm outflow-induced propagation may also be important on certain days. This is the so-called "density current" observed in tropical squall lines (Moncreiff and Miller, 1976). In cell environments with basically two-dimensional wind shear (speed but not directional shear), the downdrafts from many convective cells can form a pool of cool, rain-chilled low-level air which flows against the prevailing wind, even though each individual downdraft has downwind momentum. This low-level flow creates convergence and increased low-level moisture on the upshear-side of the convective system, as well as providing increased vertical wind shear in the cell environment. Thus, the intensity of the convective storms will be enhanced, while the storm will propagate discretely from the upshear side. In chapter 3, we will relate this concept to actual observations from July 19.

2.4 Significance of Topographic Influences on High Plains Convective Activity

The region of the High Plains immediately to the east of the Rocky Mountain foothills is a heavily populated mixture of agricultural areas and urban ceters. Mean summertime precipitation data (Fig. 5) show that much of this zone receives less summertime rainfall than either the mountains to the west or the eastern Colorado plains. High amounts of rainfall are concentrated over the highest ranges, with a minimum coinciding with South Park. A maximum extends out into the plains northeast of Colorado Springs, coinciding with the Palmer Lake Divide. As one moves east toward the Kansas border, total summer precipitation gradually increases. The dry region immediately east of the foothills is more remote from the Gulf of Mexico source of low-level moisture than areas to the east. At the same time, this region lacks the direct terrain forcing of cumulus clouds present in the mountains to the west.

A large proportion of convective precipitation which falls on the eastern Colorado plains comes from mesoscale convective systems, which often take the form of squall lines (Henz, 1975). These mesoscale convective systems occur most often in the afternoon in eastern Colorado. Thus, their initiation may often be coincident in space and time with the eastwardly propagating thunderstorm systems which have their origins in mountain thunderstorms. In this section, observations of these storms immediately east of the Rockies are examined. The development of plains mesoscale systems are documented, and possible connections with

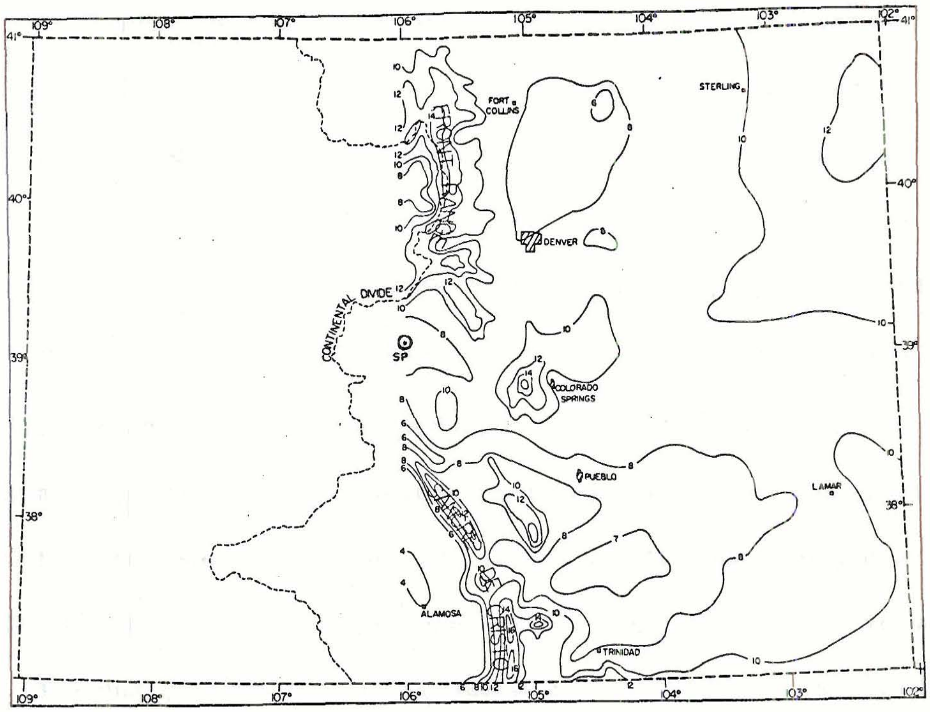


Figure 5. Colorado map showing normal May-September precipitation (1931-1960) east of longitude 106°W. Isolines are in inches (1 in. = 25.4mm). From Dirks (1969). Analysis from U.S. Department of Commerce map.

the diurnal mountain thunderstorms are suggested. Also, some proposed dynamic mechanisms for squall-line formation which occur on scales larger than that of mountain thunderstorms will be examined. Finally, the connection between these afternoon systems of the western plains and the well-known nocturnal precipitation maximum of the central Great Plains will be investigated.

The time of maximum echo generation generally occurs at about 1300 MDT for almost all mountainous areas in central and eastern Colorado (Henz, 1974). However, the frequency of echo generation is much greater over a few "hot spots" than over the remainder of the mountains and foothills. Henz found that hot spots existed well out into the plains along the Cheyenne Ridge and the Palmer Lake Divide. Among the strongest of the Front Range genesis areas is the valley of the South Platte River directly east of South Park. The north slope of the Palmer Lake Divide is an eastward extension of this hot spot. A storm moving eastward from South Park would pass through each of these regions in turn. Henz did not tabulate radar echoes over mountainous areas higher than 2.3 km elevation, due to attenuation of the radar beam by terrain features (scan elevation angle of the NWS WSR-57 radar at Limon was only $\frac{1}{2}^{\circ}$). A similar pattern exists on the east slopes of the Black Hills of South Dakota (Kuo and Orville, 1973). Radar studies there have shown an echo maximum over the highest peaks at about 1300 local time, with subsequent movement of the echo maximum downwind as the afternoon progresses.

Both precipitation and severe weather events over the High Plains were related by Henz (1974) to Front Range "hot spots". Forty-one percent of convective systems and seventy-three percent of severe weather producing systems observed in Henz' radar studies originated over "hot spots".

A two-dimensional numerical vorticity model was used by Dirks (1969) to simulate the pattern of mean flow and vertical motion in the lee of a north-south mountain barrier (the Front Range). The model predicted that return flow from large scale slope winds would create a zone of strong subsidence 50-100 km east of the mountain barrier. Farther east, the model predicted weak upward motion at the top of the boundary layer. Thus, the predicted pattern of vertical motion was somewhat consistent with the observed summer time precipitation shown in Fig. 5. Henz' (1974) and Wetzel's (1973) radar climatologies confirm the existence of a suppressed region immediately east of the mountains, and Wetzel (but not Henz) finds a moderate genesis area farther east. Both Henz and Wetzel confirm the preference of convective development for the Cheyenne Ridge and Palmer Lake Divide areas. Henz also found that many areas of the plains-foothills interface had a secondary maximum of convective development at about 1600-1800 MDT. This may be partly due to the initiation of thunderstorms by evening downslope drainage winds, which would create low-level convergence at the foot of the slopes.

The large north-to-south gradients of precipitation and radar activity, associated especially with the Palmer Lake Divide area, point out the inadequacy of a two-dimensional approach to eastern Colorado convective patterns. A recent application of the Pielke three-dimensional mesoscale model (Pielke, 1974) to the topography of Colorado was done by Hughes (1978). When initialized with an actual case study sounding (from Aug. 4, 1977), and driven by realistic surface temperatures, this model generates large scale patterns of terrain-generated convergence and divergence which are consistent with observed convective patterns, including the enhancement of vertical motion over the Palmer Lake Divide in the afternoon. However, this model failed to develop the upslope surface winds commonly observed in the afternoon.

Crow (1969) graphed the diurnal pattern of "major" precipitation events (rain > 2.5 mm/hr) for each of a series of north-to-south lines, extending from the western edge of the plains to eastern Kansas (Fig.6). He found that the daily maximum occurred at 17-1800 MDT at the western line of stations (Ft. Collins-Pueblo), 2200 MDT at the Colorado-Kansas border, and 0300 MDT (same as Central Standard Time, CST) the next day in eastern Kansas and Nebraska. Wetzel (1973) shows a similar sequence for radar echoes in eastern Colorado, with a maximum in radar echoes at 2000 MDT in eastern Colorado, compared to 2200 MDT for Crow's major precipitation events for the same region. Thus, large rainfall events occur at a later time than do all echoes in eastern Colorado. This is not consistent with the diurnal trend in static stability, since the largest storms occur after sunset, when stability would be increasing.

The well-known Great Plains nocturnal precipitation area is located in eastern Kansas and Nebraska, near the Genoa-Wichita line in Fig. 6. Thunderstorm data, stratified into quarter days (Fig. 7) demonstrate the existence of this region and also show that the High Plains of eastern Colorado are a region of rapid transition between an area of daytime convection to the west and night-time convection to the east.

The transitional nature of the region of eastern Colorado is emphasized in a rawinsonde analysis by Holzworth (1964). In this study, the maximum mixing depth, approximately the maximum altitude reached by thermally-forced parcels in the afternoon, was determined for 45 rawinsonde stations in the contiguous United States. The data were

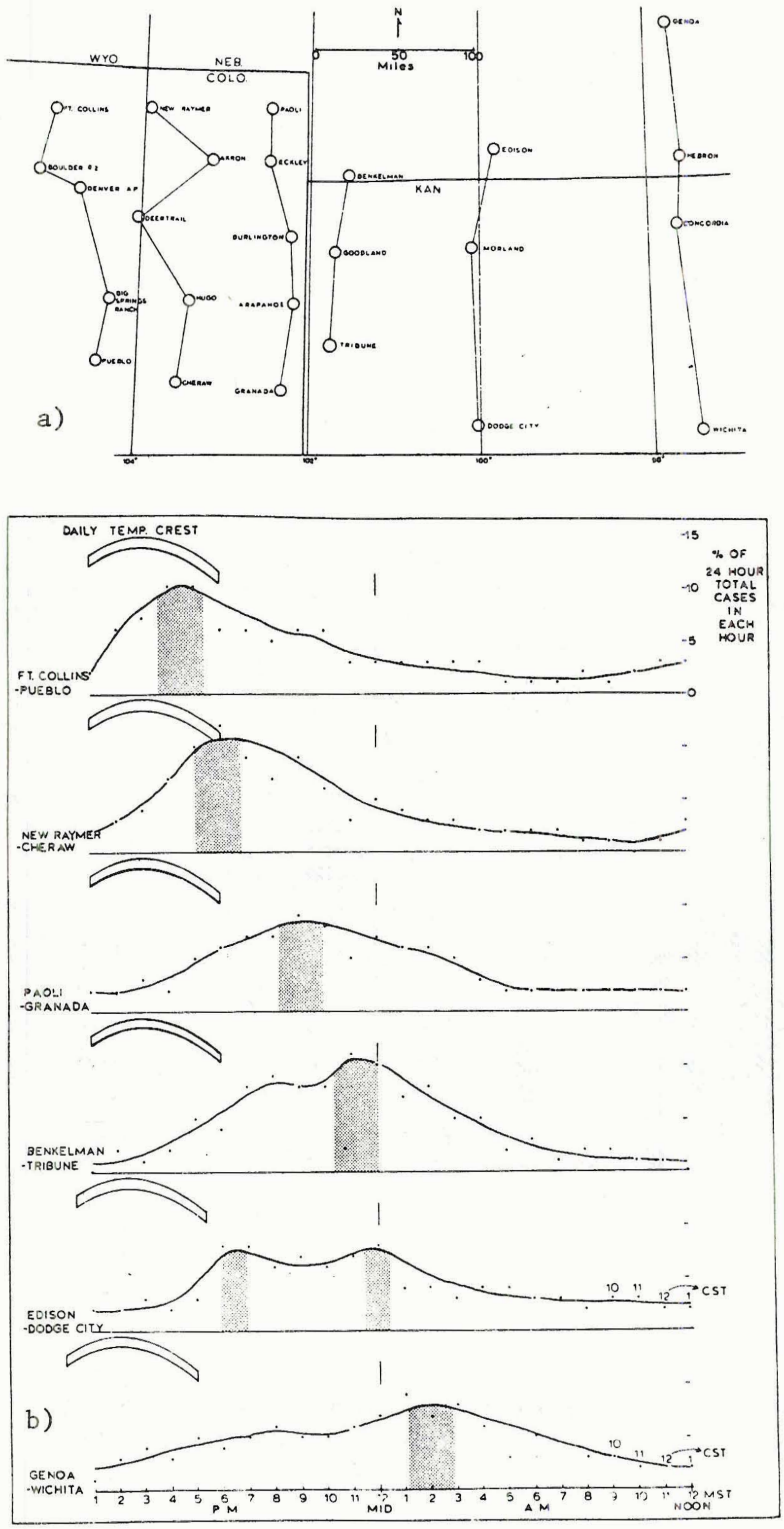


Figure 6. a) Six groups of stations with north-south orientations used in the timing analysis of convective shower activity. b) Timing of major convective activity for ten-year summary of hourly precipitation ≥ .10 inch for the six groups of stations (from Crow, 1969).

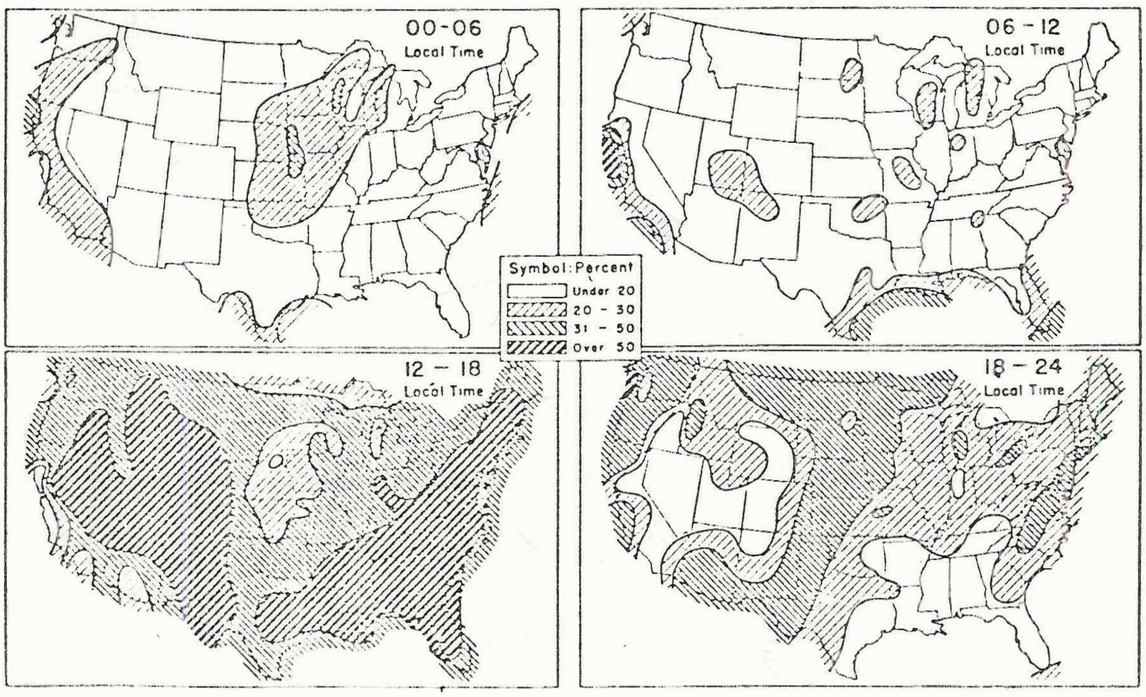


Figure 7. Percentage of summer thunderstorm occurrences per quarter day. From Hydrometeorological Report, 1947.

stratified by months. The results for July are shown in Fig. 8a. Dry, mountainous sites in the Southwest have mixing depths of over 3 km AGL while the central plains have very thin mixing layers, less than 1.5 km AGL (Denver, unfortunately ommitted from this analysis, would be expected to have an intermediate result). When the afternoon lifted condensation level (LCL) is compared to the maximum mixing depth, an interesting pattern is obtained (Fig. 8b). Even considering the high

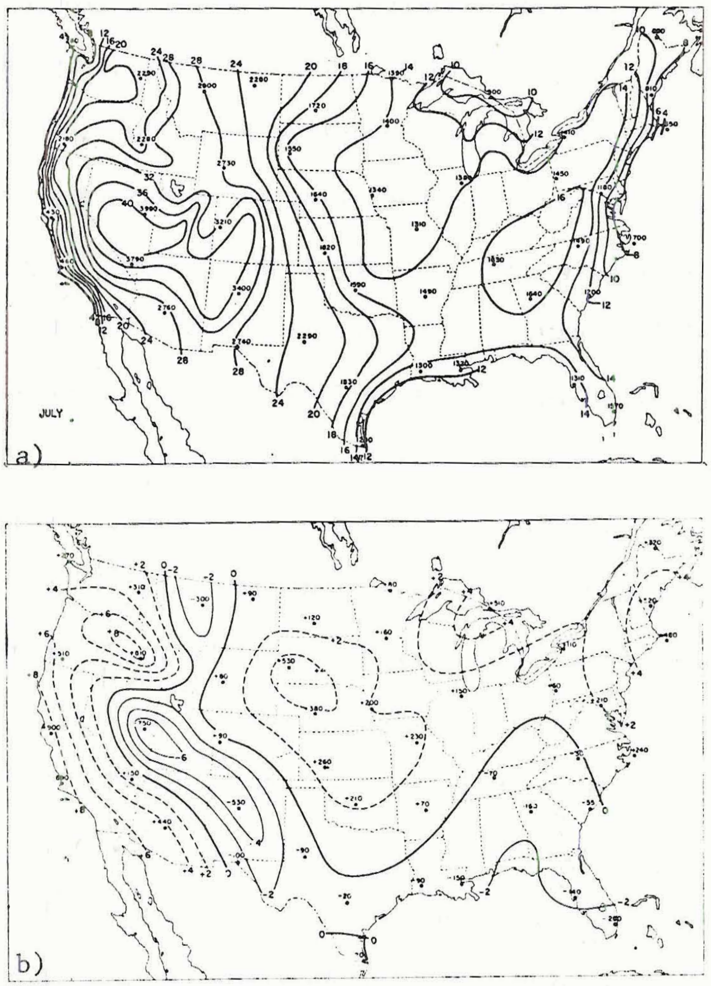


Figure 8. a) The mean maximum mixing depth (m) for July, from 10 years sounding data over the contiguous United States. b) Differences, in meters, between mean lifted condensation level and mean maximum mixing depth for July. A positive value (dashed contours) indicates that the condensation level is higher than the mixing depth. From Holzworth (1964).

values of low-level moisture present in the central plains, the LCL is above the mixing depth, while the LCL occurs well within the mixing depth for dry Southwestern locations. Thus, convective clouds in the central plains tend not to be produced by vertical thermal forcing in the summer. This result emphasizes the necessity of mesoscale low-level convergence in the creation of plains convective storms.

Wallace (1975) determined the diurnal pattern of precipitation over the U.S. by harmonic analysis of ten years of hourly precipitation data. He found that all precipitation events, heavy rainfall, and thunderstorms have a strong diurnal peak at 1700 MDT at Denver (June-August data). As one moves eastward, heavy rainfall (>2.5 mm/hr) has a progressively later peak, on about the same schedule as Crow's data (Fig. 6). All precipitation events (including trace events) peak later in the night and have less diurnal modulation, while thunderstorms peak earlier and are more strongly modulated. Thus, in eastern Kansas, all precipitation peaks at 0500 LST, heavy rain peaks at 0300 LST, and thunderstorms are most prevalent at midnight. This would indicate that while the <u>occurrence</u> of precipitation is completely out of phase with the diurnal cycle of static stability, the <u>severity</u> of convection is more in phase with the solar heating cycle.

While the occurrence of thunderstorms in the mountains can be strongly correlated with thermodynamic factors caused by diurnal heating, the rise of plains mesoscale systems must be controlled by mesoscale dynamic features. Bleeker and Andre (1951) used 2 years of 4 times daily Pibal data for August to compute divergence and convergence at three different levels (Fig. 9). They found that strong

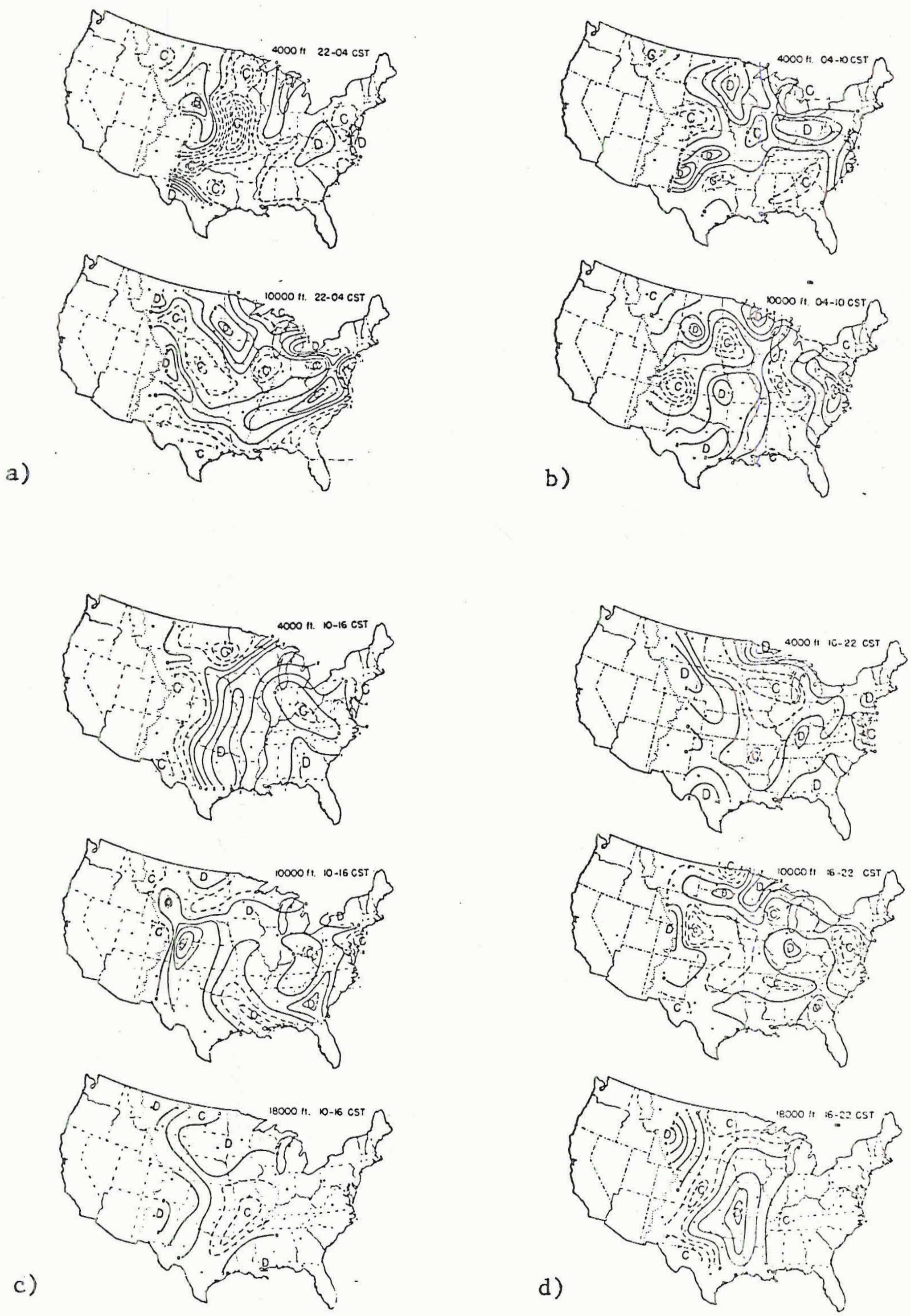
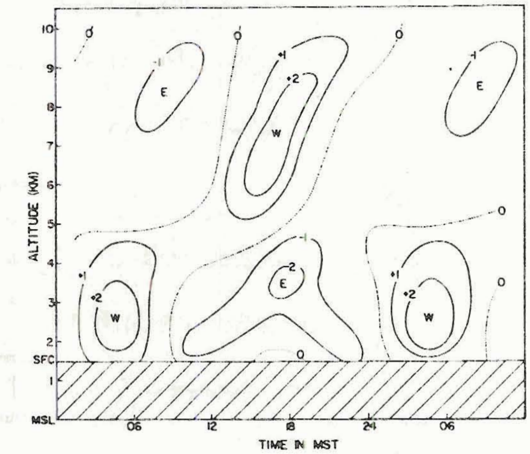
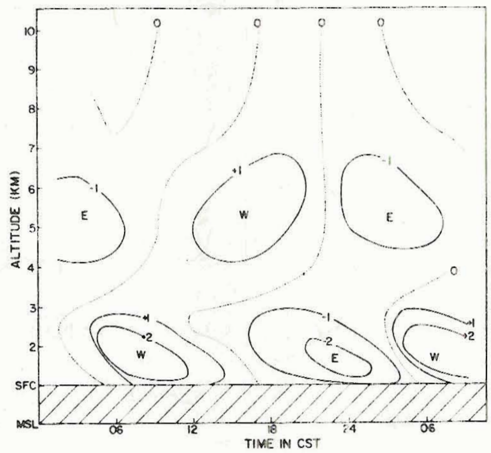


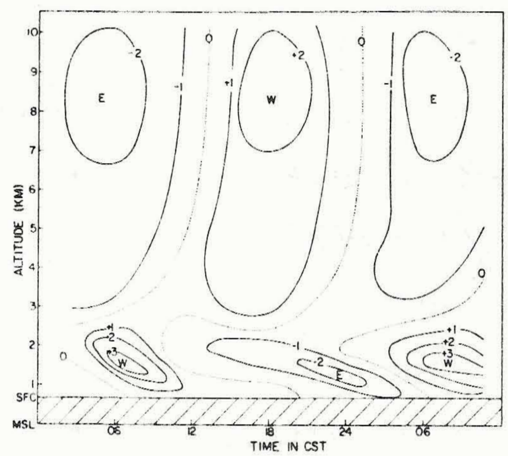
Figure 9. Change in divergence between two successive sets of balloon wind observations, for all days in August 1947 and August 1948. a) 2200-0400 CST (Central Standard Time; same as MDT, or Mountain Daylight Time) or nighttime. b) 0400-1000 CST, early morning. c) 1000-1600 CST, midday. D) 1600-2200 CST, evening. Levels are 1.2 km (4000 ft.), 3.0km (10,000 ft.) and 5.5km (18,000 ft.). From Bleeker and Andre (1951).



Denver



Amarillo



Dodge City

Figure 10. Westerly component of the mean departure vector as a function of altitude and time, derived from 4 x daily balloon flights. Data for 28 undisturbed summer days at Denver, Colorado; Amarillo, Texas; and Dodge City, Kansas. From Dirks (1969).

divergence was generated at low levels throughout the Great Plains during the day (Fig. 9c, 1000-1600 CST), with a maximum of divergence in eastern Colorado at 10,000 ft (3.0 km). During the late afternoon and early evening (Fig. 9d, 1600-2200 CST), convergence was generated at 10,000 ft (3.0 km) (near the top of the PBL) in the plains, with a maximum in northeastern Colorado. Throughout the night (Fig. 9a, 2200-0400 CST), strong low-level convergence was generated over the central plains, with divergence at low and middle levels over the western plains.

Serial rawinsonde data taken at Fort Worth, Texas (Hering and Borden, 1962) and at Denver, Amarillo, Texas, and Dodge City, Kansas (Dirks, 1969) reveal diurnal oscillations at both lower and upper levels. The westerly departure from the mean as a function of time is shown for three stations in Fig. 10, for 28 relatively undisturbed summer days. The diurnal pattern at Dodge City and Amarillo lags that at Denver by 5-6 hours. Notice also that the depth of the lower oscillating cell is greatest at Denver, such that the 3 km level is the level of greatest oscillation at Denver, while this level is above the oscillating cells at the other stations. This agrees qualitatively with Fig. 8, where the largest generation of convergence and divergence at 3.0 km occurs over eastern Colorado, but not farther east. Wetzel (1973) used serial rawinsondes from the NHRE area in northeastern Colorado to show a similar diurnal wind shift for "moderate" convective precipitation days ("dry" and "wet" days were dominated by westerly (dry) and southeasterly (wet) synoptic winds). By 1800 MDT on moderate days, winds had shifted through north to almost due east in the layer surface (890 mb) -740 mb ($\sim$1.5 km deep). Modahl (1978) used 3 years of NHRE data to show a similar result (shift from west to east at low levels), but by his stratification of days, hailfall days had the greatest shift during the day, and the greatest westward moisture advection.

Dirks (1969, chapter VII) reviewed the many possible atmospheric waves which could serve to modulate mesoscale convective activity in the lee of the Rockies. Of particular interest were internal gravity waves at the top of the planetary boundary layer and mountain lee waves. Dirks concluded, however, that no wave phenomenon could be found which persisted across such a broad range of conitions as the observed convective pattern. A detailed look at the many types of atmospheric waves is beyond the scope of this paper.

A related boundary layer phenomenon which may be significant to the propagation process is the so-called "low level jet". A persistent feature of the central U.S., especially the southern plains, is a low-level maximum in wind speed. Blackadar (1957) observed that, in many cases, this maximum occurs before sunrise at the top of the well-developed nocturnal inverson (typically 500 m AGL). Blackadar showed that, under conditions of constant geostrophic flow, the excess of wind speed over geostrophic at night was similar to the deficit of wind speed below geostrophic during the day. He derived an inertial oscillation which would have the greatest amplitude just above the inversion, where the difference between daytime and nighttime shear stress would be greatest. This oscillation has a period of one-half pendulum day or 12hr/sin ϕ (where ϕ = latitude), which would bring the inertial and geostrophic components into phase 8-12 hours after sunset in the central U.S., creating a supergeostrophic wind speed maximum. The oscillation would create a departure vector from geostrophic which would rotate in a clockwise sense. This clockwise rotation has been observed by Hering and Borden (1962), Bonner (1968), and many others.

Low-level wind maxima occur most frequently in the area of western Kansas and Oklahoma (Bonner, 1968, Fig. 11). When simultaneous wind data are plotted for a low horizontal surface (such as the 850 mb level), a coherent pattern similar to an upper level jet stream is sometimes revealed. On the northern, or downstream side of the jet maximum, low-level convergence occurs, which can be correlated with nocturnal thunderstorm activity (Pitchford and London, 1962). Bonner (1968) shows that these jet maxima tend to recur in a relatively small area in Kansas and Oklahoma (Fig. 12). Thus, the downstream convergence associated with the low-level jet occurs in roughly the same area as nocturnal showers (Fig. 7) and low-level convergence (Fig. 8) already mentioned. This horizontal jet profile and the vertical low-level wind maximum are both referred to as a "low-level jet" by different authors.

While the observations of the low-level jet seem to relate well to the observed nocturnal precipitation maximum, a complete explanation of the jet and its relationship to the west-to-east pattern of mesoscale propagation have not been forthcoming. Blackadar (1957) mentions that the phase of his free inertial oscillation depends on the initial departure vector from geostrophic at sunset. Extending this concept, we observe that an easterly component of the direct slope wind, coupled

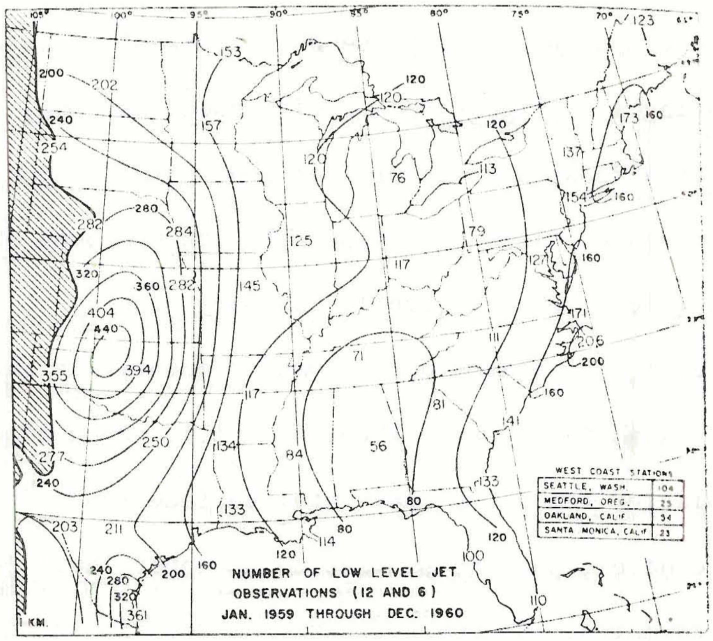


Figure 11. Number of low-level wind maxima, here defined as a wind speed of over 12 ms^{-1} occurring below 1.5 km AGL, with a decrease of wind speed above the maximum of 6 ms^{-1} or more, during two complete years, for soundings at 0600 MDT and 1800 MDT. (A total of 1462 soundings at each station). From Bonner (1968).

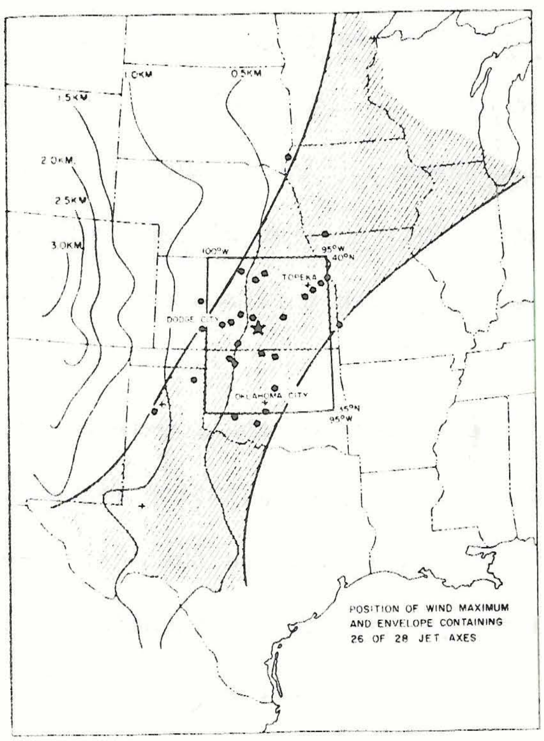


Figure 12. Location of core of the horizontal low-level jet, for 28 selected cases. The star represents the median location of all the jet cores. The envelope contains 26 of the 28 jet axes. Terrain contours in km are included. From Bonner (1968).

with frictional turning of the wind, could result in an easterly turning of the basic southerly current along east-facing slopes during the day. Thus, the western plains, which are steeper than those farther east, would have a departure vector from geostrophic which would be advanced in a clockwise direction at sunset. This would mean that the maximum southerly jet would occur earlier farther west, creating a convergence zone which would move from west to east.

Lettau (1967) observed that Blackadar's idea had two basic shortcomings. It predicted the time of wind maximum to be a function of latitude, contrary to observation, and it failed to explain the geographic distribution of low-level wind maxima (Fig. 11). Lettau proposed the "thermo-tidal wind", which would apply over any large terrain slope. This was an extension of Backadar's theory, to include a diurnal oscillation of the geostrophic wind due to heating on even very slight terrain slopes (1:400 at O'Neill, Neb.). This would tend to keep the period of the oscillation at 24 hours at all latitudes. Data showing a diurnal oscillation of the east-west height gradient at 850 mb in the plains (Dirks, 1969) tend to support Lettau's ideas, as does the 24-hour periodicity in winds found by Hering and Borden (1962) and Bonner (1968), among others. Using an assumed correlation between terrain elevation and geostrophic wind, Lettau achieved very good agreement with the O'Neill data set in the lowest 1.5 km, for a dry, undisturbed day (Lettau, 1967).

This discussion of topographic influence on plains convective activity is by no means comprehensive or exhaustive. The subject is far too complex for an adequate treatment here. We merely wish to suggest a number of ways in which terrain-induced flow patterns may help explain the observed pattern of convective activity.

In the following chapters, case study analyses of two separate operational days from the SPACE 1977 data set are examined for evidence of various terrain-induced effects on the convective precipitation process. The analyses are partitioned into three basic phases. The first phase is the morning evolution and destabilization of the PBL in South Park. The second phase documents the appearance of orogenic cumulus clouds and thunderstorms, and their patterns of translation and propagation. The third phase includes the development of mesoscale convective systems and their eastward movement across the high plains. This phase was observed in only one of the case studies, August 4. In the final chapter, the information from this chapter and the knowledge gained from the case studies are combined into a conceptual model of terrain-induced convective precipitation patterns. Finally, it is suggested what possible further analysis of South Park data might reveal, and also the form future field projects might take.

3.0 19 JUL 1977 CASE STUDY

One of the two initial case study days chosen was 19 July 1977. This day was characterized by extremely intense, long-lived thunderstorms which lasted until late in the day, but did not propagate eastward onto the plains. The storms formed within South Park and moved generally northward with the mean flow, at relatively slow speeds. CP-3 radar reported echo tops of over 15 km, and reflectivities of at least 55 dBz within South Park. Although a few similar large cells formed in the Denver and Fort Collins areas, the plains generally remained cloud-free throughout the day, with extreme high temperatures of over $35^{o}C$.

This day was chosen for intensive analysis because it should provide a detailed data set, including triple-Doppler radar, of intense, quasi-steady-state thunderstorm systems. These data should be suitable for initiation of and comparison with three-dimensional numerical thunderstorm models. Thus, this day serves as a basis for comparing and contrasting the character of mesoscale organization on eastward propagating days with that on days when mesoscale storms occur, but do not propagate eastward. The storms occurred generally in an environment of light winds and low vertical wind shear. The data which are used to describe these sytems consist mainly of rawinsondes, surface meteorological station data (PAM), and radar PPI scans. It is demonstrated that the intensity of convection within South Park on July 19 was largely dependent on boundary layer Pacific moisture which advected eastward across the Rocky Mountains during the day.

3.1 19 July 1977 - Synoptic Situation

On July 18 and for several days preceding it, most of the United States, including the Southwest, was under a vast subtropical high pressure center. 500 mb winds were light and usually southerly in the Southwest, bringing deep Pacific moisture inland. East of the Rockies, the air under the high was very dry. On July 18, 500 mb heights generally fell along the Pacific coast, displacing the high center into western Kansas and enhancing the southwesterly "monsoonal" flow. East of the Rockies and in South Park, very hot, dry air remained. The surface pressure pattern showed a broad low pressure center in South Dakota with a surface trough extending along the eastern edge of the Rockies to southeastern Colorado.

Within South Park, deep convection was suppressed throughout the day on July 18 due to lack of boundary layer moisture (<5 gm kg^{-1}). However, thunderstorm activity was detected by satellite and radar in a band extending from western Colorado to eastern Wyoming. Around 1800 MDT, 18 July, moist, northerly and northwesterly flow penetrated into the northwest corner of the Park, with a few thunderstorms visible over the mountains to the northwest. This pattern of convective activity and surface flow was repeated the next day, except that the band of strong convective storms shifted farther east to include the South Park area. Satellite infrared (IR) pictures show the convective intensity decreasing during the night in the northern Colorado mountains.

The synoptic situation for Colorado on the morning of July 19, 1977 is shown in Figs. 13 through 15. At 500 mb (Fig. 13), the center of the subtropical high had retreated somewhat, into eastern Kansas

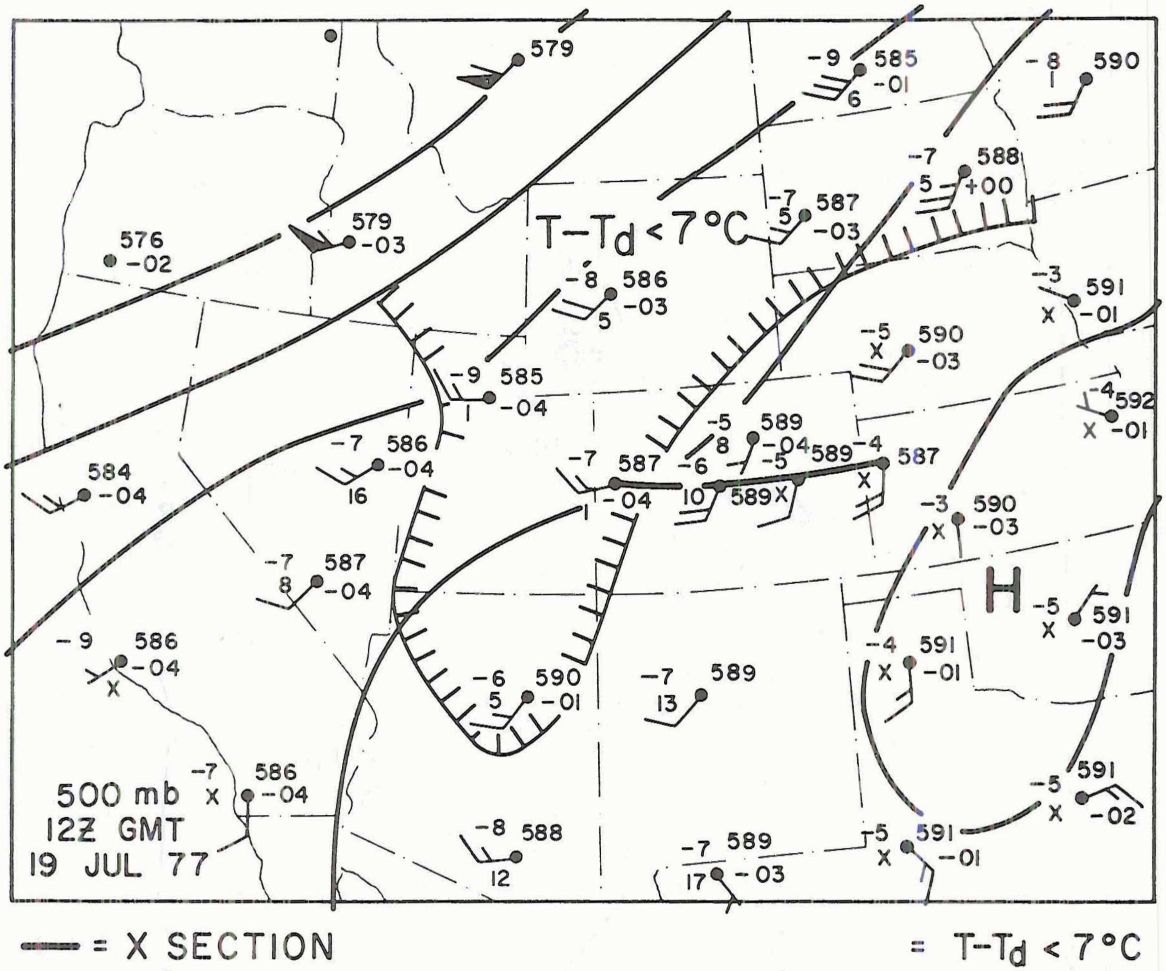


Figure 13. 500 mb analysis for 0600 MDT (1200 GMT), 19 July, 1977. Areas with a dew-point depression ($T-T_d$) less than 7^oC are marked. Stations used in cross-sections are connected with a bold line.

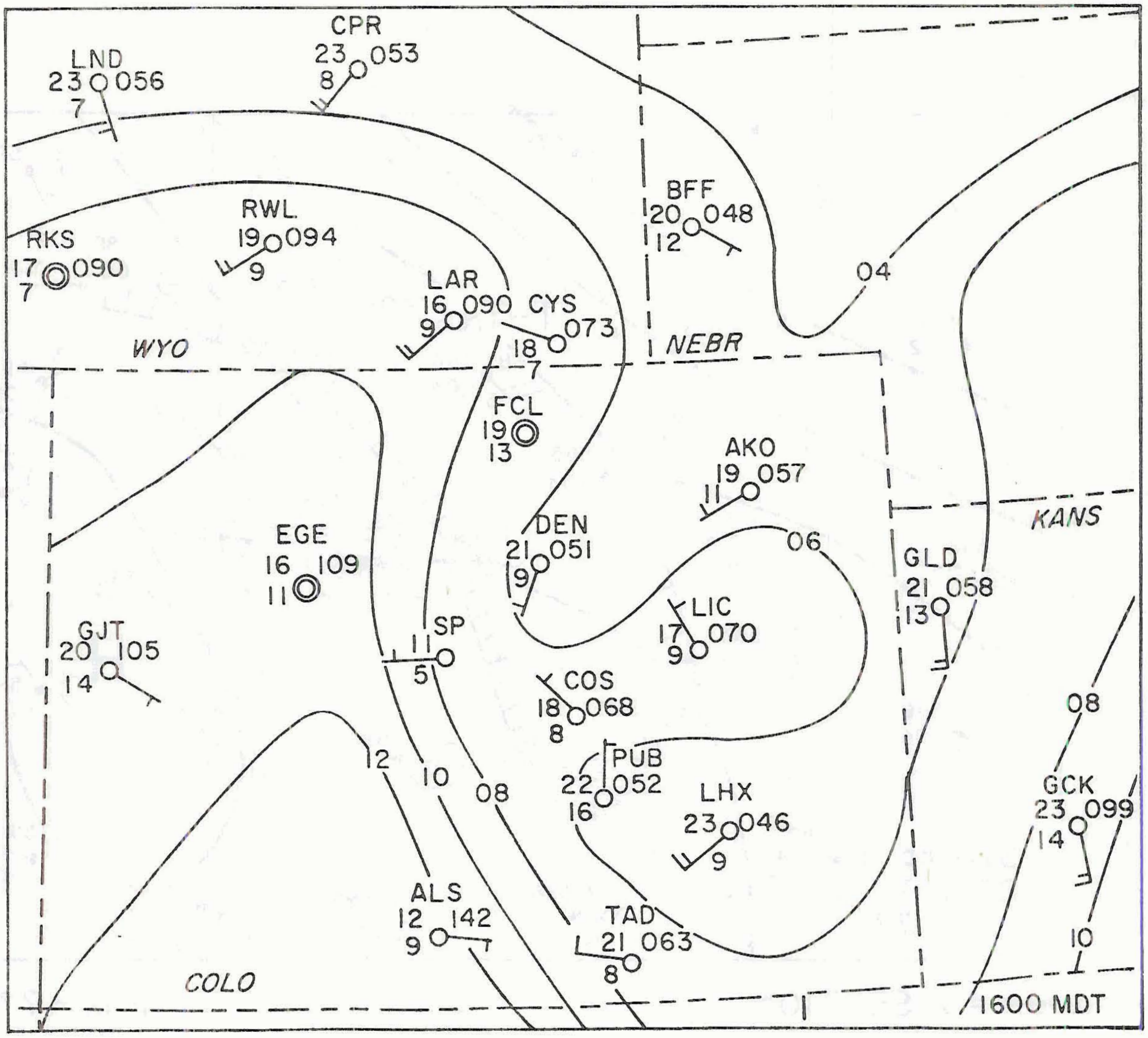


Figure 14. Mesoscale surface analysis for 0600 MDT, 19 July, 1977. Temperature and dew-point in Deg. C. Note pressure trough in eastern Colorado.

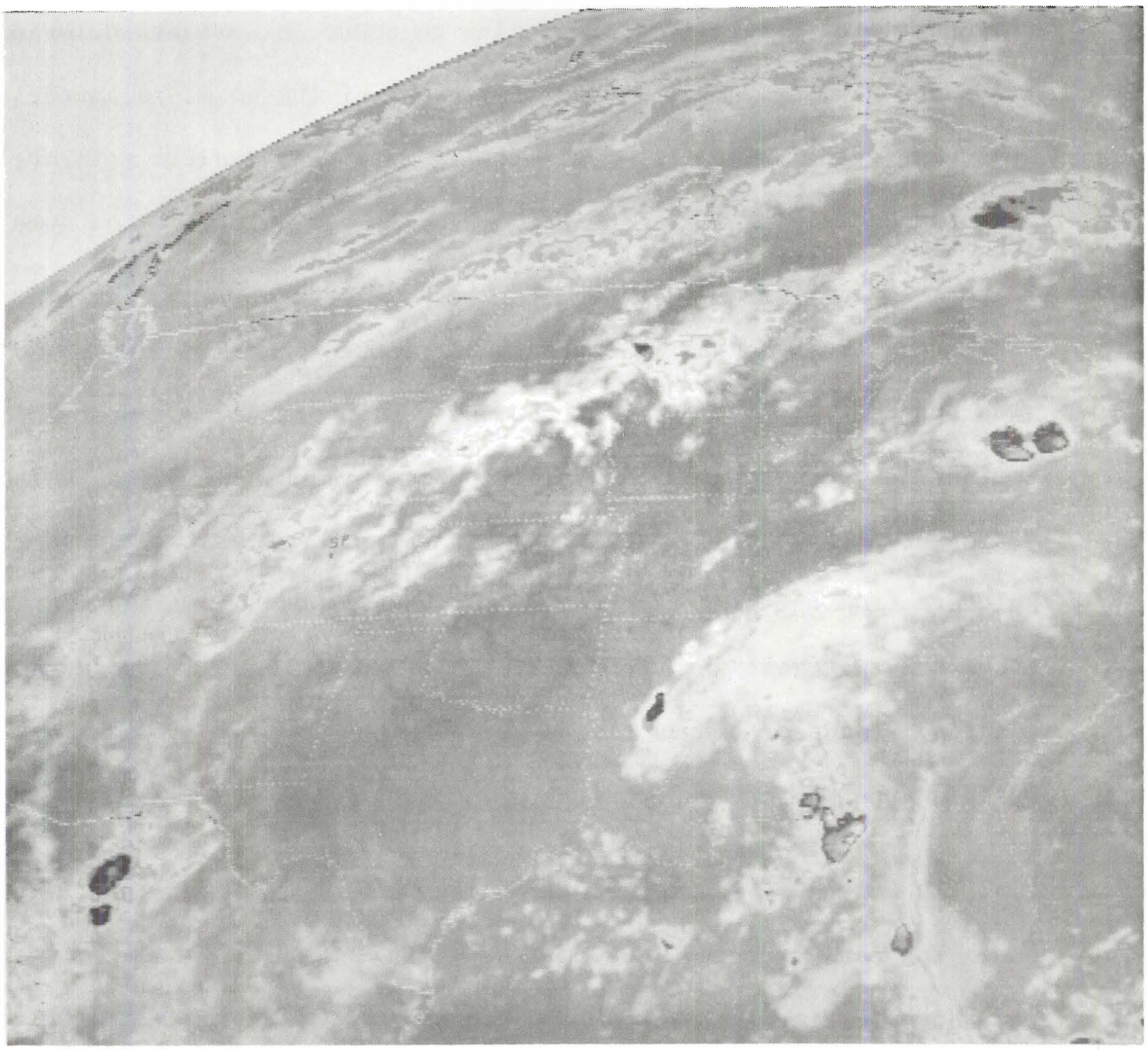


Figure 15. Infrared (IR) Satellite image of western U.S., 0600 MDT, 19 July, 1977. Dotted lines are state boundaries. Various shades represent different IR temperatures according to the succession drawn at the top of the figure (temperature decreasing toward the right). Thus, large cold cloud tops representing intense convective cells appear as black or black-outlined areas within the white mass of lower clouds.

and Oklahoma. The region of high humidity at 500 mb ($T-T_d < 7^{o}C$) extended from northern Arizona northeastward in a band to Wisconsin and beyond, with convergent flow seeming to occur in northern Colorado and southern Wyoming. This eastward movement of the moisture advection pattern served to import substantially more deep Pacific moisture onto the eastern slopes of the Colorado Rockies during the day on July 19.

On the surface (Fig. 14, data from National Weather Service stations) the presence of a pronounced trough covering eastern Colorado was apparent, an extension of the surface low pressure center which remained in South Dakota. Winds within the trough were light, while stronger surface winds prevailed to the south and east. The satellite picture from the same time (Fig. 15) shows a band of clouds extending from the southwest through western Colorado and northeastward into Canada. Bands of cirrus clouds were present in eastern Colorado, including the South Park area.

3.2 19 July 1977 - Mesoscale Sounding Data at 1200 GMT

The early morning (1200 GMT) sounding on 19 July from South Park is shown in Fig. 16. The surface inversion was very shallow (20 mb) with high moisture values (7.4 gm kg^{-1}) in the lowest 40 mb of the sounding. Raising this moisture to the cloud condensation level (CCL), a potential cloud base of 575 mb was obtained, relatively low for South Park, where the nearby mountains extend up to about 600 mb, or over 4 km MSL. Lifting a saturated parcel from cloud base along a moist adiabat, about 2^{o} of convective instability are obtained, also relatively unstable. However, when mixed through a realistic mixing depth

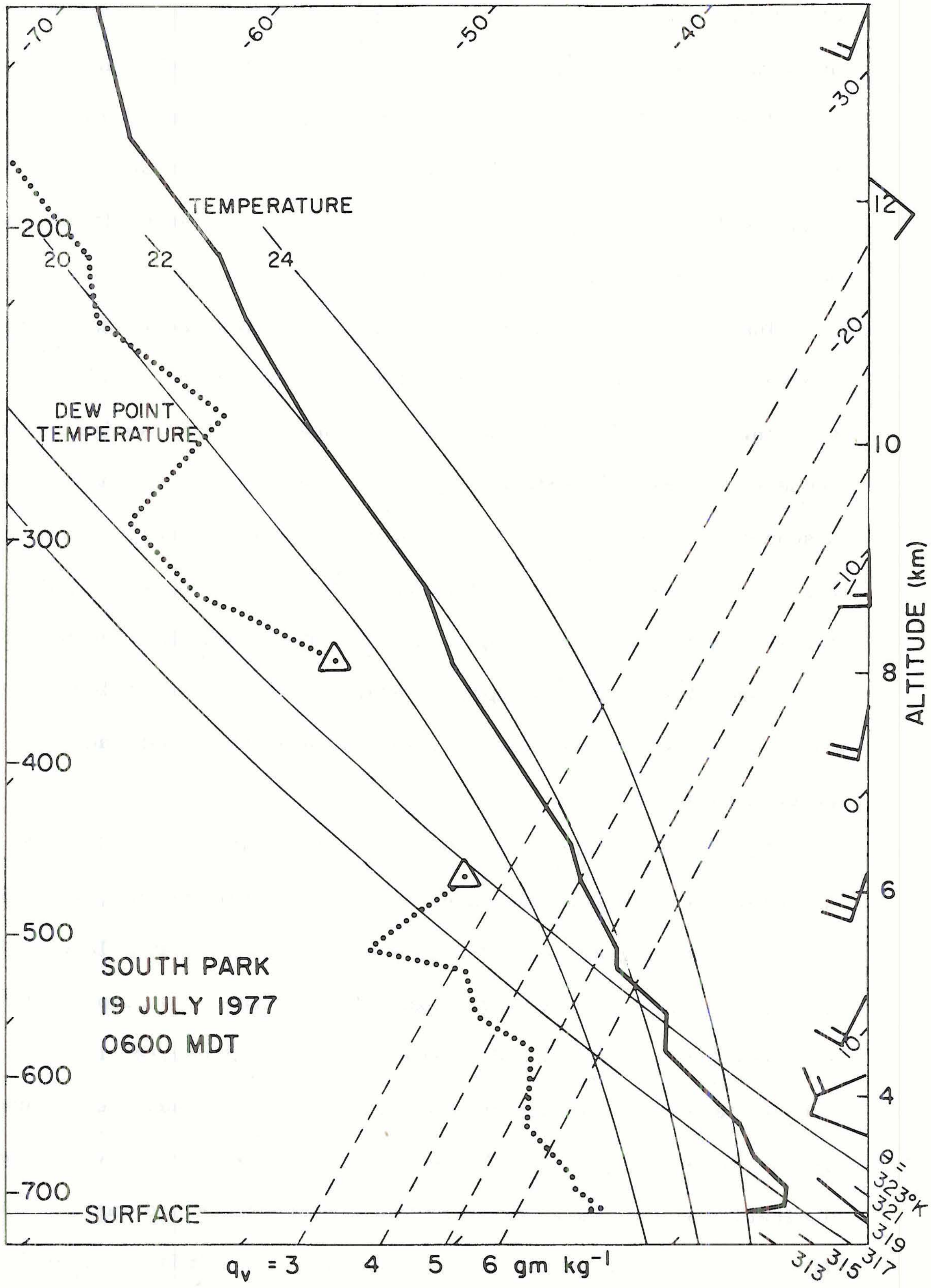


Figure 16. South Park sounding for 0600 MDT (1200 GMT), plotted on skew-T log-P diagram.

of 140 mb, this sounding produces a mixed layer q_v of 6.0 gm kg^{-1} and almost no 500 mb instability. No significant stable layer was observed at the 400-500 mb level. Increased humidity at 350 mb indicates the level of the cirrus deck observed from the ground and by satellite. Light northeasterly downslope surface winds backed smoothly to light southerly winds in the upper levels.

The pattern of moisture advection across the mountains becomes more apparent on construction of an east-west cross section using 1200 GMT soundings (Fig. 17). The four stations used for this analysis are connected in Fig. 13 with a heavy line. Stable layer boundaries and a schematic terrain cross section are drawn as dark solid lines in Fig. 17. Lines of constant potential temperature (θ) are light solid lines, constant mixing ratio (q_v) lines are dashed, and rawinsonde winds are plotted as wind barbs. Analysis is omitted at low levels where data are unrepresentative, such as near the Front Range and the upper Arkansas valley.

Fig. 17 shows that, by 1200 GMT on 19 July, the Grand Junction sounding was strongly influenced by deep moist convection, with deep moisture, veering winds, and only a weak elevated stable layer. Contrastingly, the eastern plains exhibited a strongly suppressed pattern. Both the Limon and Goodland soundings had a deep neutral layer (to 590 mb) above the surface inversion, wtih a strong subsidence inversion in the layer 500-590 mb. The neutral layer was warmest over Limon, indicating the thermal troughing which appeared on the surface map (Fig. 14). The extremely light winds over Limon indicate that it was

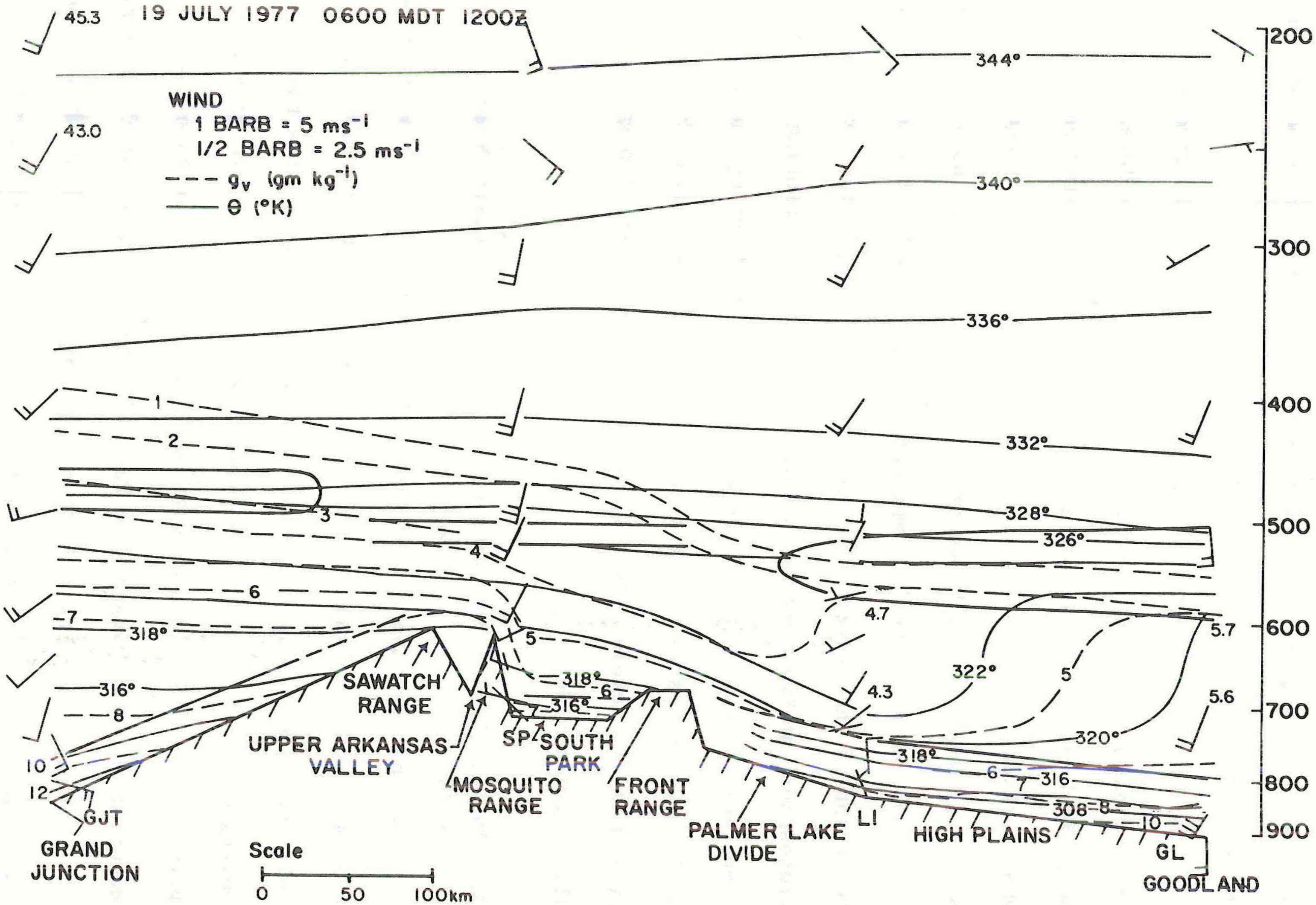


Figure 17. East-west cross-section including soundings from Grand Junction (GJT), South Park (SP), and Limon (LI), Colorado and Goodland (GL), Kansas. Solid contours are potential temperature (^{o}K) and dashed contours are water vapor mixing ratio (gm kg^{-1}). Terrain elevations and stable layer boundaries are marked with bold lines. Valid for 0600 MDT, 19 July 1977.

near the trough axis. The dryness of the air in the neutral layer (q_v = 4.5 - 5.5 gm kg^{-1}) would suggest that little or no moist convection would occur in the plains on 19 July.

The South Park sounding showed characteristics intermediate between the dry eastern and moist western soundings. The low-level analysis in South Park on Fig. 17 is partially derived from PAM surface data, which show surface mixing ratios of 7-8 gm kg^{-1} at the high ridge of the Mosquito Range, driven by westerly winds of 10 ms^{-1}. Both South Park and Limon had a northerly component to their low-level winds, a manifestation of the eastern Colorado trough. Winds in the moist middle troposphere at Grand Junction were more westerly, insuring that the deep Pacific moisture would be advected eastward during the day. As will be demonstrated in later sections, strong moisture advection occurred at low levels, where it was influenced by the topography, throughout the day.

3.3 19 July 1977 - Evolution of the Morning Planetary Boundary Layer (PBL)

We have described in section 2.2 the complexities associated with even an idealized model of PBL evolution over mountainous terrain. On July 19, we had the additional complications arising from the strong moisture and pressure gradients which existed in the vicinity of South Park. In this section, we will use rawinsonde and surface data to document the deepening of the PBL prior to cumulus cloud formation.

Surface data from the PAM network are shown in Fig. 18 for 0600, 0800, and 1000 MDT. Potential temperatures (^{o}K), mixing ratios (gm kg^{-1}), and winds are plotted at each working station. Many of the

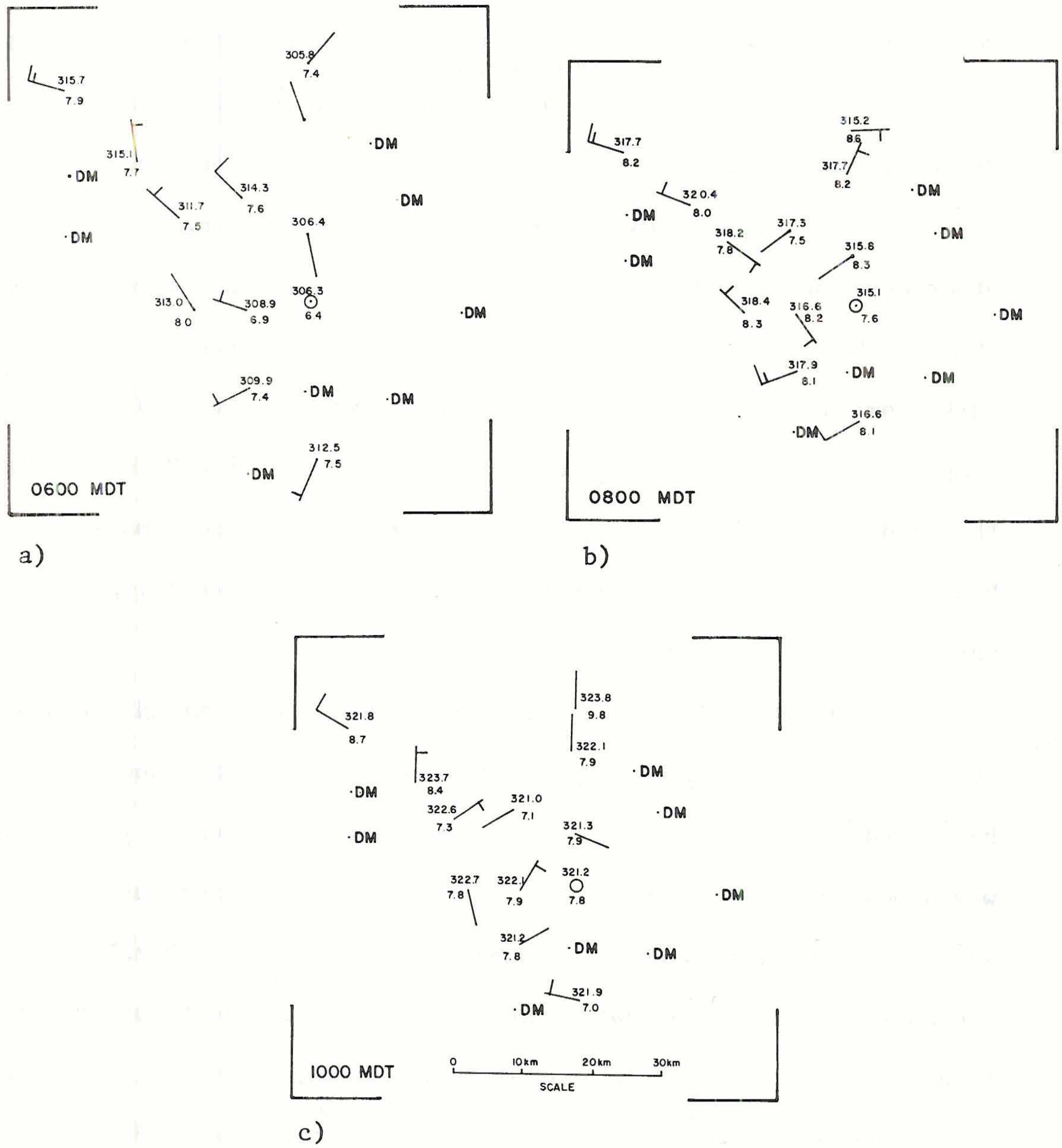


Figure 18. PAM surface data taken in South Park. a) at 0600 MDT, b) at 0800 MDT and c) at 1000 MDT, 19 July, 1977. Five-minute averaged potential temperature (^{o}K), water vapor mixing ratio (gm kg^{-1}) and winds are plotted at each station. DM means data missing for that time.

more remote PAM stations were not sending data due to base transmitter problems during the morning. At 0600 MDT (Fig. 18a), nighttime drainage flow had served to pool the coldest air in the low-lying river valleys. Mixing ratios were already unusually high compared to other days in South Park, 6-8 gm kg^{-1}. Note that at ridge-top level (Sta. 5, Mosquito Pass), very moist air was being advected into South Park from farther west, driven by westerly winds. By 0800 MDT (Fig. 18b), temperatures had increased faster in the center of the Park, decreasing the gradients across the Park. Mixing ratios had become more uniformly high at about 8 gm kg^{-1} throughout the Park. Winds were light and variable.

The 1000 MDT rawinsonde (Fig. 19) showed a well mixed PBL up to 600 mb. This air mass had θ of 321^{o}K, mixing ratio of about 6.5 gm kg^{-1}, and very light winds. Between 600 and 530 mb was a layer which was almost neutral, with a θ of 324^{o}K and much less moisture (3-4 gm kg^{-1}). Winds in this layer were much stronger, about 10 ms^{-1}, from the southwest. Thus as the day progressed, we might expect surface winds to have picked up from the southwest and surface moisture to decrease, as the PBL entrained this layer. 1000 MDT surface data (Fig. 18c) show somewhat decreased surface moisture at most stations, except for increased mixing ratios on the northwestern edge of South Park. The amount of PBL moisture observed with the 1000 MDT rawinsonde was marginal for deep convection. The low-level moisture apparently present to the north and west of South Park (as deduced from satellite pictures and the GJT sounding), however, would indicate a very unstable atmosphere, with potential cloud tops to at least 12.5 km.

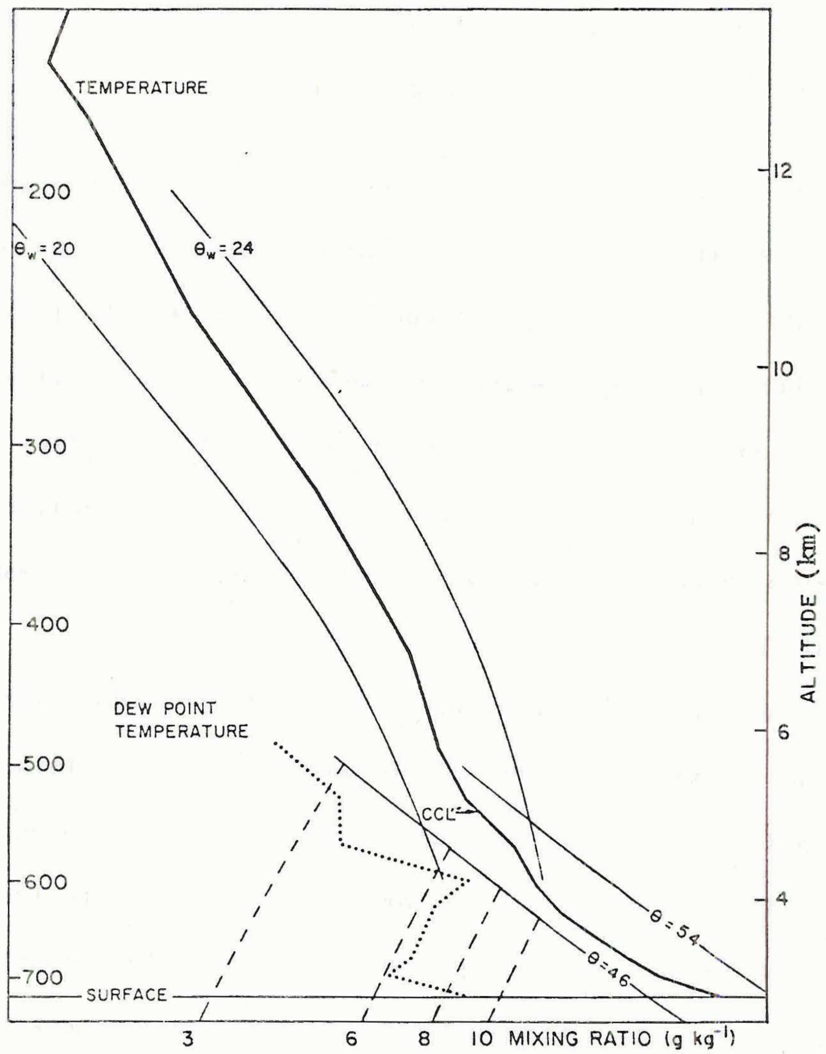


Figure 19. South Park sounding of 1000 MDT, 19 July, 1977, plotted on skew-T log-P diagram.

Most of South Park and the plains to the east remained cloud free until after 1200 MDT. Surface potential temperatures were over 325^{o}K in most of the Park, with slowly decreasing mixing ratios. Radar, satellite, and visual observations all reported increasing cumulus activity in the mountains west and north of the Park. In the plains, extreme temperatures were also reached (>35^{o}C) with light winds in the eastern Colorado surface trough area.

3.4 19 July 1977 - Early Afternoon Mountain Thunderstorms

The first precipitating radar echoes appeared in South Park around 1200 MDT, as the atmosphere continued to destabilize under strong surface heating. In this section, we will show that widespread deep, moist convection did not develop in most of South Park until after 1530 MDT, due to lack of PBL moisture. The thunderstorms which did develop on the edges of South Park are explained as resulting from local "hot spots" and moisture advection.

The rawinsonde launched at 1246 MDT revealed a strongly heated boundary layer up to the 500 mb level (Fig. 20). This layer had θ of 342.5^{o}K and a mixing ratio of only 5.3 gm kg^{-1}. Boundary layer winds were light, veering from easterly at the surface to 190^{o} at 500 mb. A sharp inversion occurred at 400 mb (7.0 km MSL) probably caused by a locally produced subsidence field near a cumulonimbus cell (see Fig.21). A mixing ratio of 7 gm kg^{-1} would be necessary to break through this inversion and initiate deep thunderstorm activity.

Shortly after 1230 MDT, the CP-3 radar began recording data. At about the same time, the PAM network became fully operational, providing surface data from up to 20 different locations at any one time.

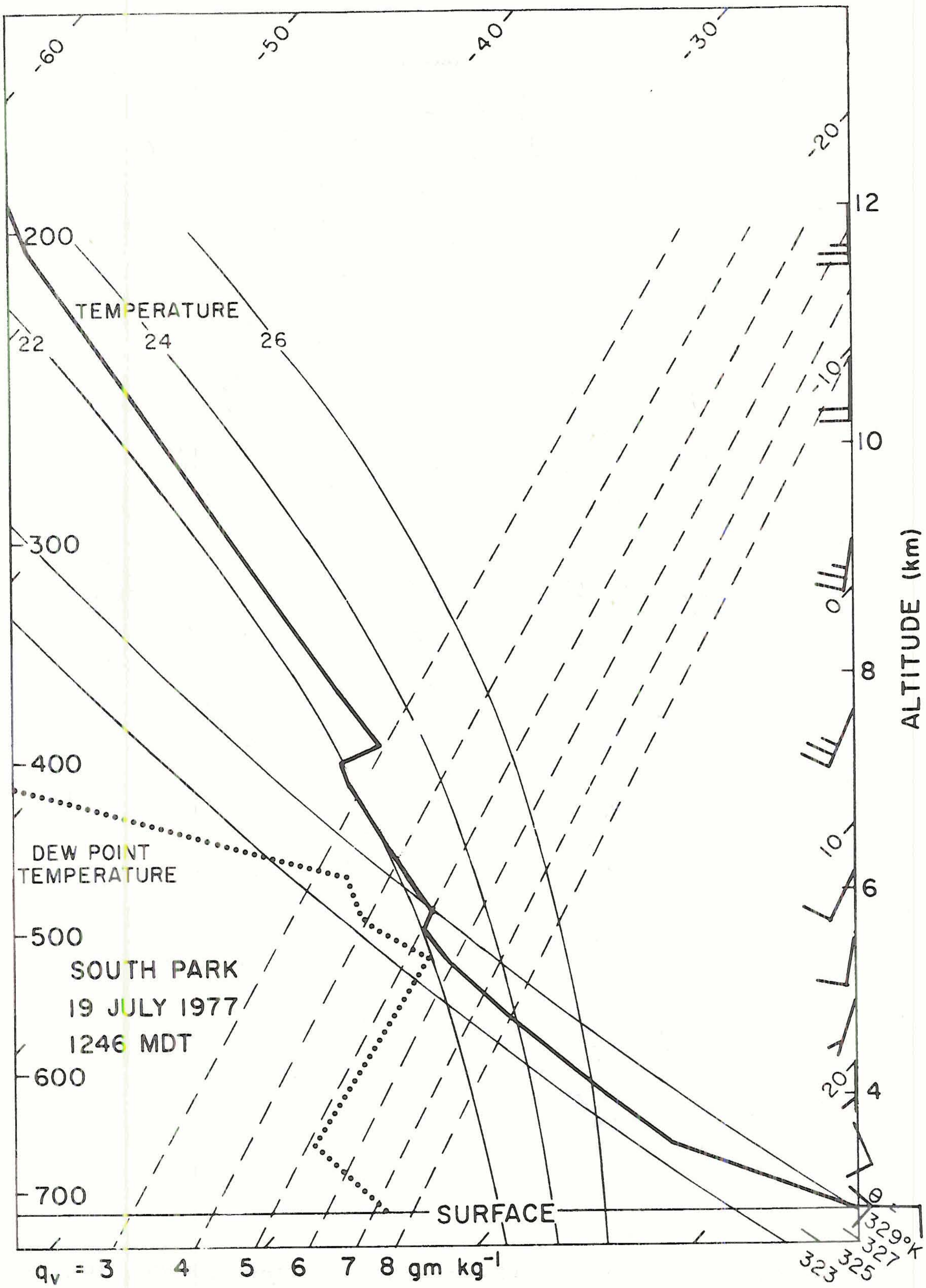


Figure 20. South Park sounding of 1240 MDT, 19 July 1977, plotted on skew-T log-P diagram.

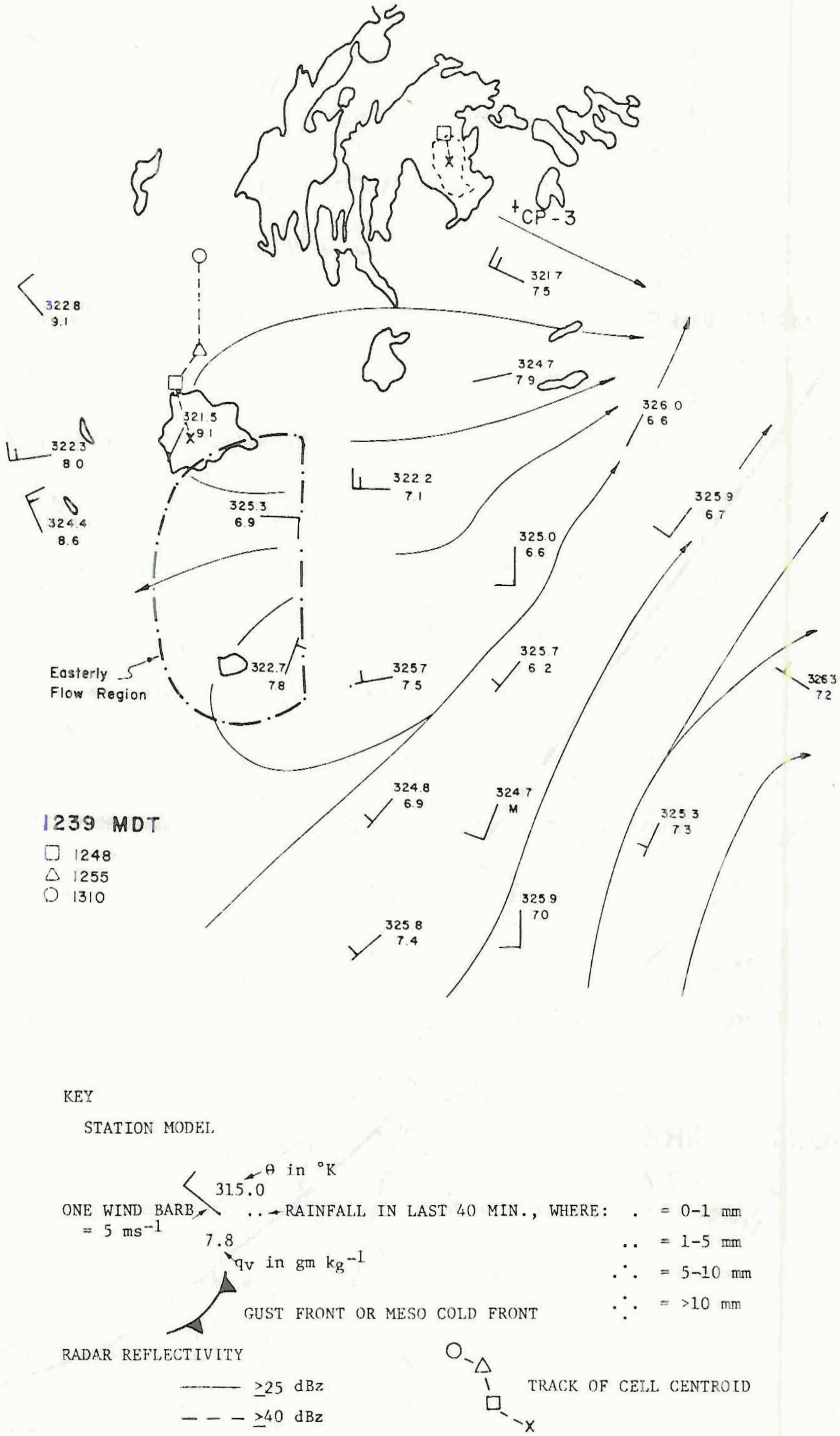


Figure 21. Composite PAM-CP-3 radar plot for 1239 MDT, 19 July 1977. Surface data as in Fig. 18. Radar contours are 5.5° constant elevation scans, projected onto a horizontal surface. Solid contours are 25 dBz, dashed contours are 40 dBz. Key to other symbols is given above.

In Fig. 21 and subsequent figures, PAM surface winds, θ, and q_v are superimposed with Plan Position Indicator (PPI) scans from CP-3. The radar contours are taken from 5.5° constant elevation scans, projected onto a horizontal plane. Solid contours are 25 dBz, inner dashed contours are 40 dBz. The path of the echo maximum for succeeding times is represented by a series of small symbols (square, triangles, etc.). Table 1 correlates observed dBz levels with precipitation intensities. It will prove especially useful in later sections when data from several radars will be used to depict a single storm. On each PAM-radar composite, a subjective streamline analysis has been done to represent general flow directions.

Table 1. Table relating Limon NWS radar summary contour number and storm descriptors (TRW-, etc.) to echo reflectivity (dBz) 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 dBz	Rainfall Rate at Surface mm/hr.
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. 21 shows the earliest available PAM-radar overlay, for 1239 MDT. A large area of convective echoes was present on the north edge of the Park, with a strong cell just west of CP-3. Another extensive echo occurred over PAM station #8 about 10 km northwest of the base site. These two locations were found by Huggins (1975) to be the likeliest places for first echoes to form. Comparing Fig. 21 with the 1246 MDT sounding (Fig. 20), we can see that the easterly surface wind present on the sounding existed only in a fairly small area (perhaps 10 x 20 km) directly east of the Mosquito Range. In this area, easterly slope winds produced by a mountain-plains type interaction may have been able to overcome the moderate ambient winds. The easterly wind would create low-level convergence on the eastern slope of the Mosquitoes, producing the "hot spot" thunderstorm present in Fig. 21. The easterly wind would also act as a barrier, keeping the moist westerly flow observed at ridge top out of the rest of South Park. Hence, mixing ratios through most of South Park continued to decrease under strong heating.

The thunderstorms shown in Fig. 21 moved almost due north at about 5 ms^{-1}, apparently steered by the southerly winds aloft. By 1333 MDT (Fig. 22), a large group of cells had formed just west of the base site, on the eastern slopes of the Mosquitoes. A north-south line of much more intense thunderstorms was present just north of Hoosier Pass in the Blue River valley (located in Fig. 2). At least one of these cells originated in South Park. It was observed to intensify greatly as it approached Hoosier Pass from the south. Range Height Indicator (RHI) radar scans synthesized from PPI scans (Knupp,

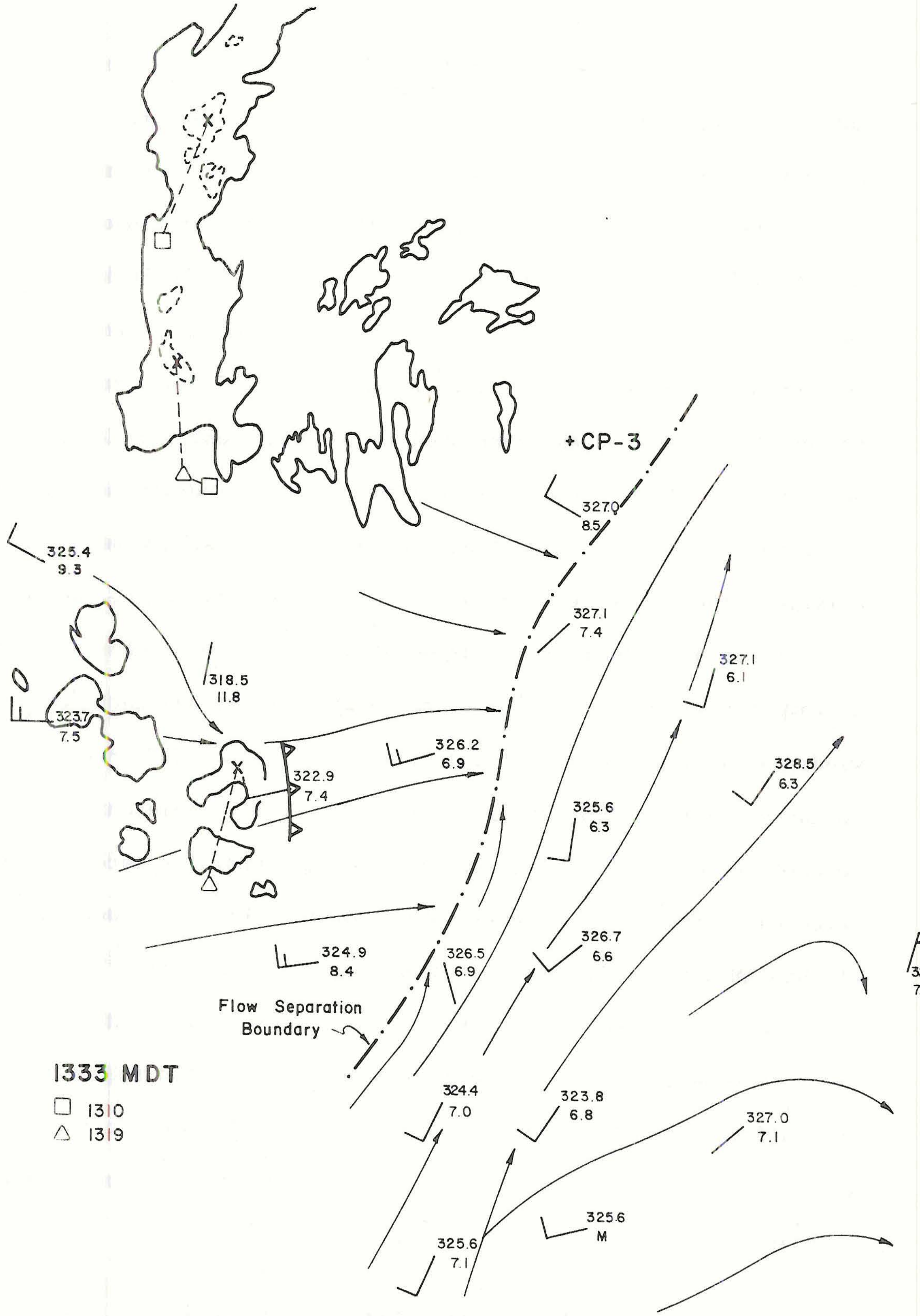


Figure 22. Same as Fig. 21, for 1333 MDT.

et al. 1978) show that these cells had echo tops of at least 12.5 km MSL; the cells within South Park had tops of only 7-8 km. This indicates that the increased boundary layer moisture ($q_v \sim 8$ gm kg^{-1}) needed to support very deep thunderstorms, as indicated by rawinsonde data, was available in the Blue valley just northwest of the Park. PAM data in Fig. 22 indicate that this moisture was being advected across the mountains by westerly winds. The remainder of South Park, excluding the north and west edges, continued in the southwesterly flow, with decreasing moisture and extremely high surface temperatures. Limon radar for 1330 MDT revealed that the Hoosier Pass storms were part of a large mesoscale convective band which extended 150 km to the northeast.

An air mass boundary and associated line of confluence with dry southwesterly winds to the east and moist westerly and northwesterly winds to the west is indicated in Fig. 22. By 1452 MDT (Fig. 23), this boundary had moved only about 10 km farther east. Numerous small radar echoes continued to appear, but penetrating downdrafts were not yet detected at the surface. Notice that one station in the southeast corner of the PAM network had shifted to an easterly wind. This flow pattern subsequently affected the entire eastern edge of South Park. It was probably caused by a large-scale easterly upslope wind resulting from the surface thermal low pressure in South Park compared to the plains to the east. Similar easterly winds are often observed in the afternoon in South Park.

3.5 19 July 1977 - Late Afternoon Mesoscale Thunderstorm Line

While the onset of very deep convection in South Park was being delayed until about 1600 MDT, a number of mesoscale factors were

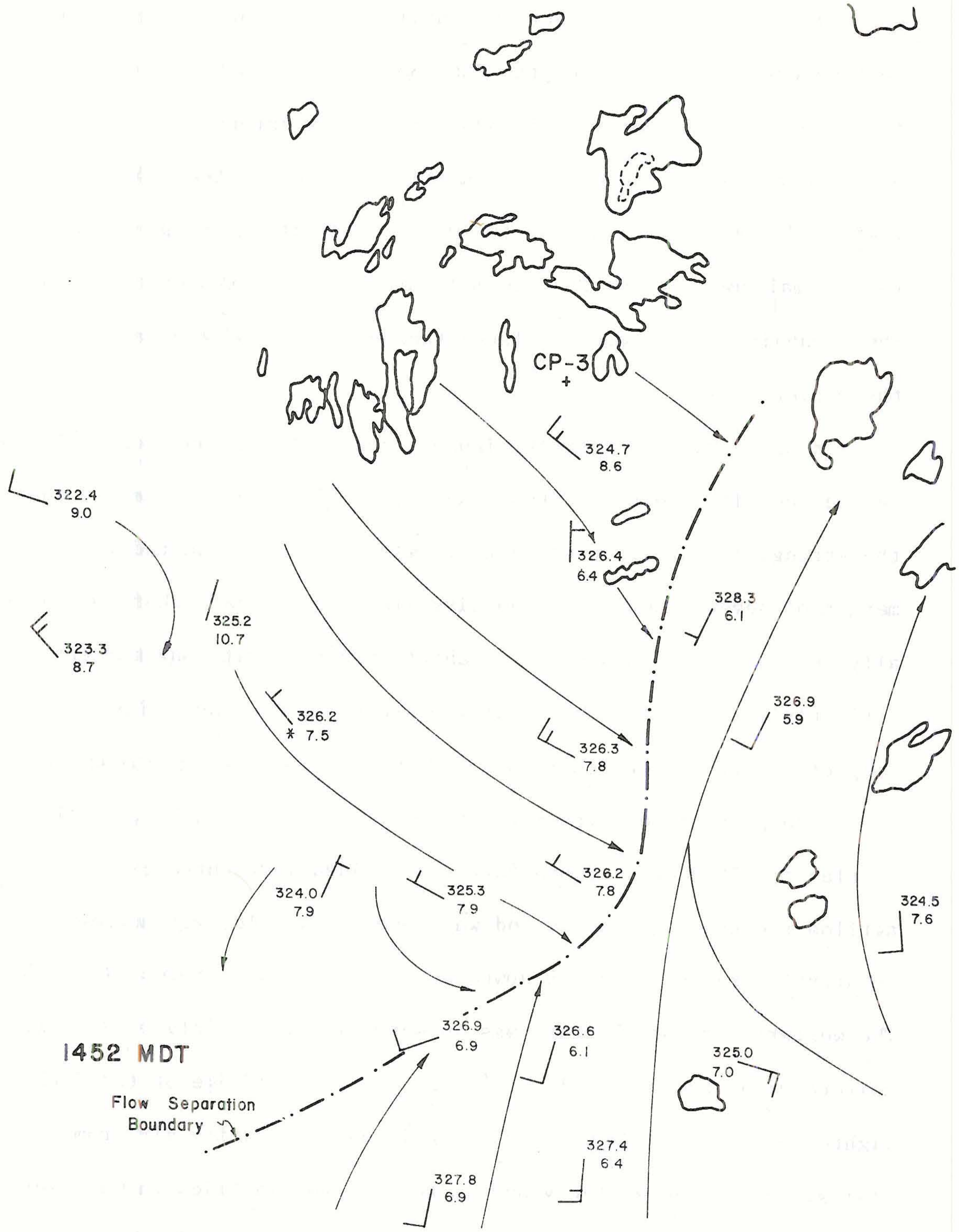


Figure 23. Same as Fig. 21, for 1452 MDT.

combining to decrease convective stability in the area. Strong surface heating continued to deepen the PBL, both in the Park and on the plains to the east. The eastern Colorado surface low intensified during the day, due to the continued strong heating. Winds on the 1444 MDT Limon rawinsonde were very light up to 400 mb, indicating the presence of the thermal low. Strong Pacific moisture continued to advect across the mountains, and large, isolated thunderstorms appeared as far east as the Denver area.

In South Park, extremely vigorous convection began around 1530 MDT in the foothills north of CP-3. Knupp, et al. (1978) observed that the strongest convective element, labeled cell C2, resulted from a merger of several smaller convective elements. A hail shaft was visually observed near this storm at about 1600 MDT, with maximum echo reflectivities of at least 58 dBz. Unfortunately, the PAM network was completely out of service from 1530 MDT until shortly after 1600 MDT.

A complex set of circumstances is revealed by Fig. 24, a PAM-radar overlay for 1623 MDT. South Park was divided into three distinct airflow regions. The north end was covered by cold, wet northerly air, apparently originating with downdrafts from intense storms C1 and C2. The western part of the Park was in warm, moist westerly winds, with uniform wind speeds of 7-10 ms^{-1}. At the eastern edge of the Park, lighter easterly winds were bringing in somewhat drier air from the plains. Where the easterly and westerly flows collided in the center of South Park, a line of convective cells was rapidly developing, oriented in a direction of about 160^{o}.

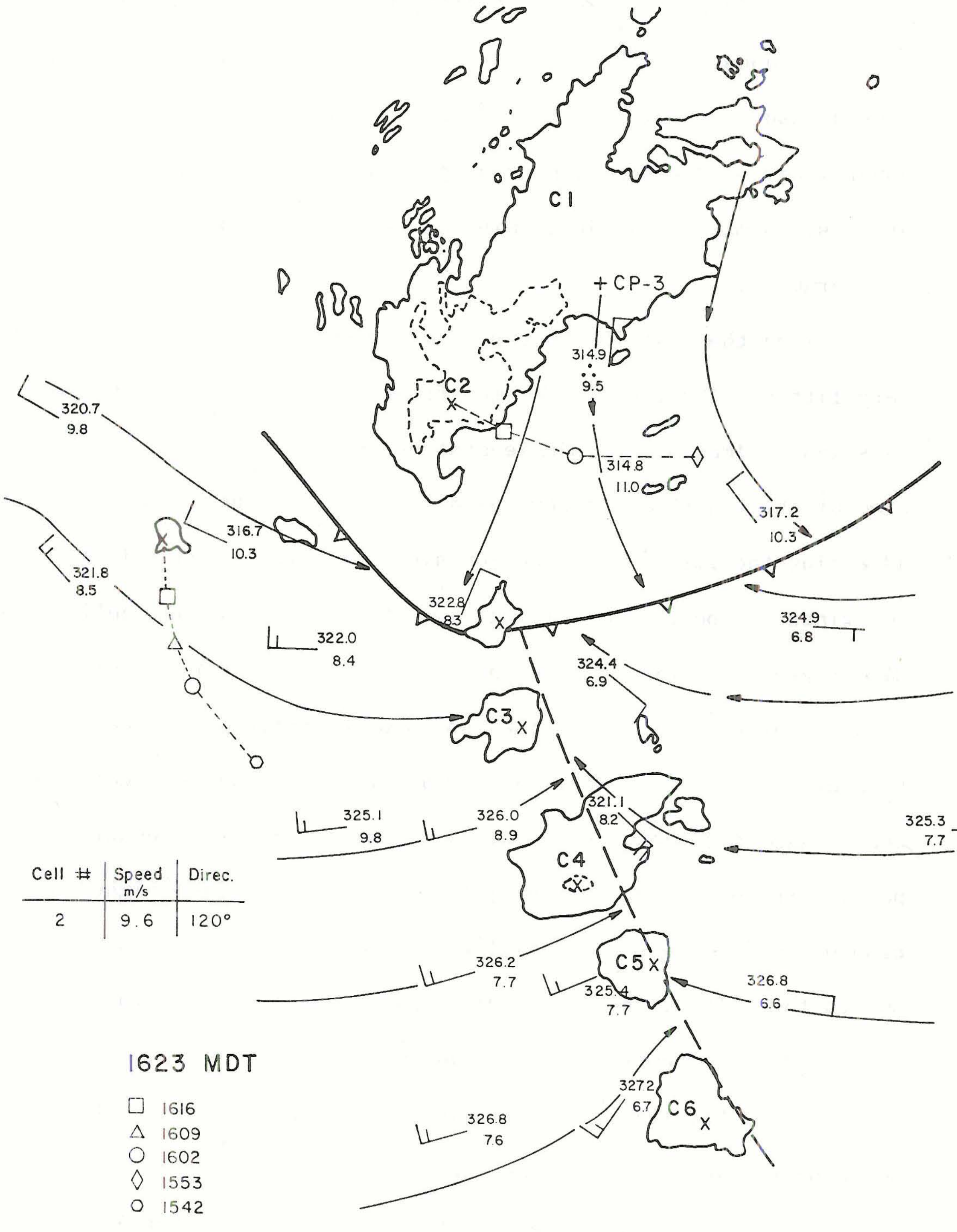


Figure 24. Same as Fig. 21, 1623 MDT. Individual convective cells are labeled C1, C2, etc. Averaged speed and direction of the reflectivity core of certain selected cells are tabulated in the lower left corner.

Cells C3-C6 all had central reflectivities of about 35-40 dBz, and were moving from a direction of 160°, along the line of echoes, at speeds of about 5 ms^{-1}. Cell C2, much bigger and more intense than the others, had been moving from 100-120°, or 50-70° to the left of the mean upper winds. C2 was moving at a speed of 10 ms^{-1}. This cell produced at least 20 mm of rain in 15 minutes at PAM station #28 (the northernmost).

During the next 15 minutes, the northerly meso-cold front moved very little. The location of the frontal boundary on all the PAM-radar maps was estimated from single-station surface data by determining the time of the windshift, accompanied by a rapid temperature drop, and advecting the gust front location along with the speed and direction of the winds behind the gust front. By 1638 MDT (Fig. 25), cells C3 and C4 had grown rapidly in size, and in intensity to over 45 dBz. Surface winds under cell C4 and farther south were southerly, as was the direction of cell motion. Temperatures in this air fell somewhat, indicating the possibility that the southerly surface winds were downdrafts transporting the entrained southerly momentum downward from higher up in the clouds. Cell C3 was north of the frontal boundary and was moving 20-30° to the left of the upper winds. East and west from the cell line, the convergent flow pattern continued.

By 1702 MDT (Fig. 26), the meso-cold front had moved about 20 km south on the west side of the convergence line, traveling at 8 ms^{-1}. In succession, cells C4, C5, and C6 had intensified to over 40 dBz reflectivity as the frontal winds approached, with cells C4 and C5 decaying rapidly as they passed well behind the front. Precipitation

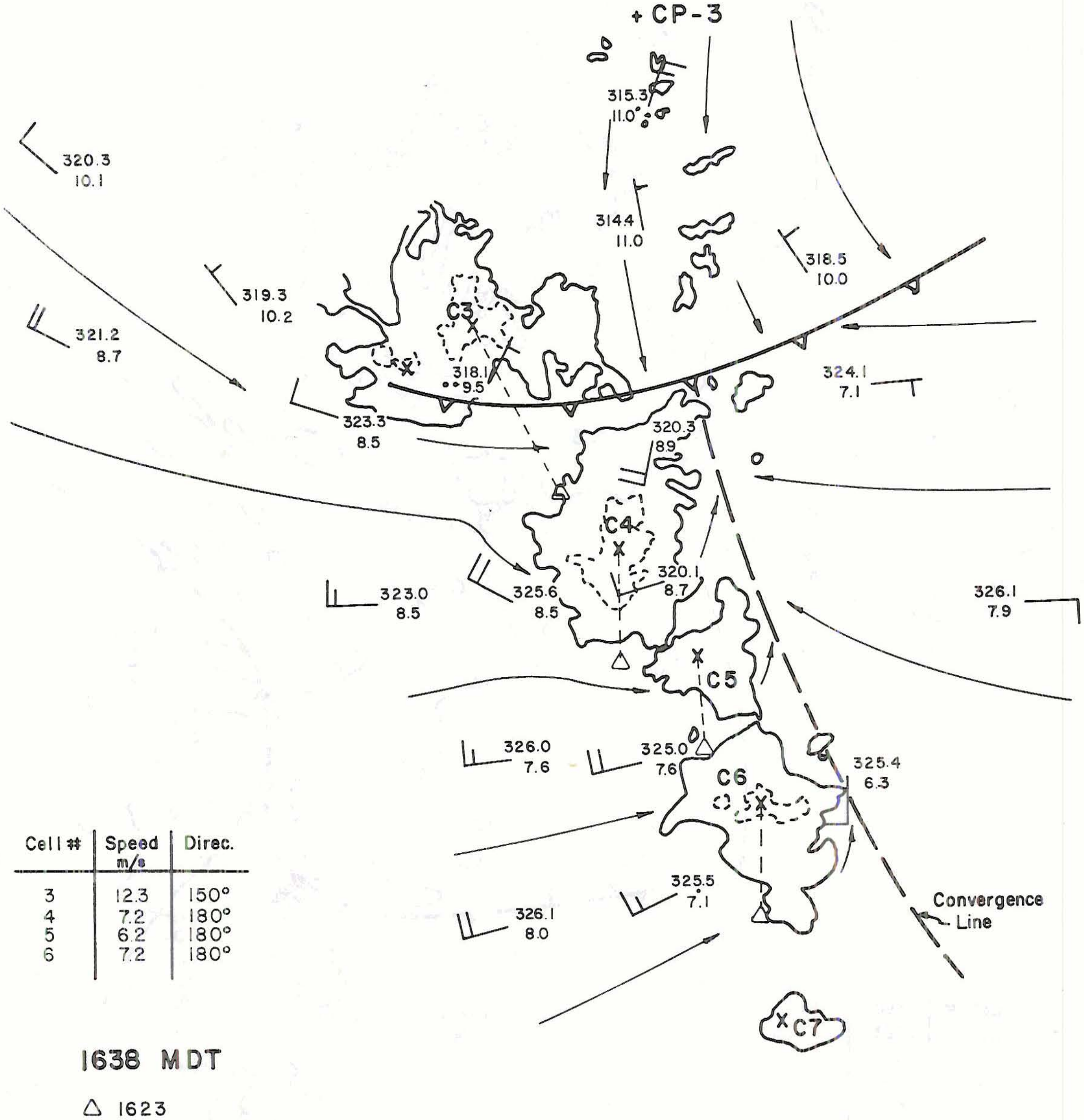


Figure 25. Same as Fig. 24, for 1638 MDT.

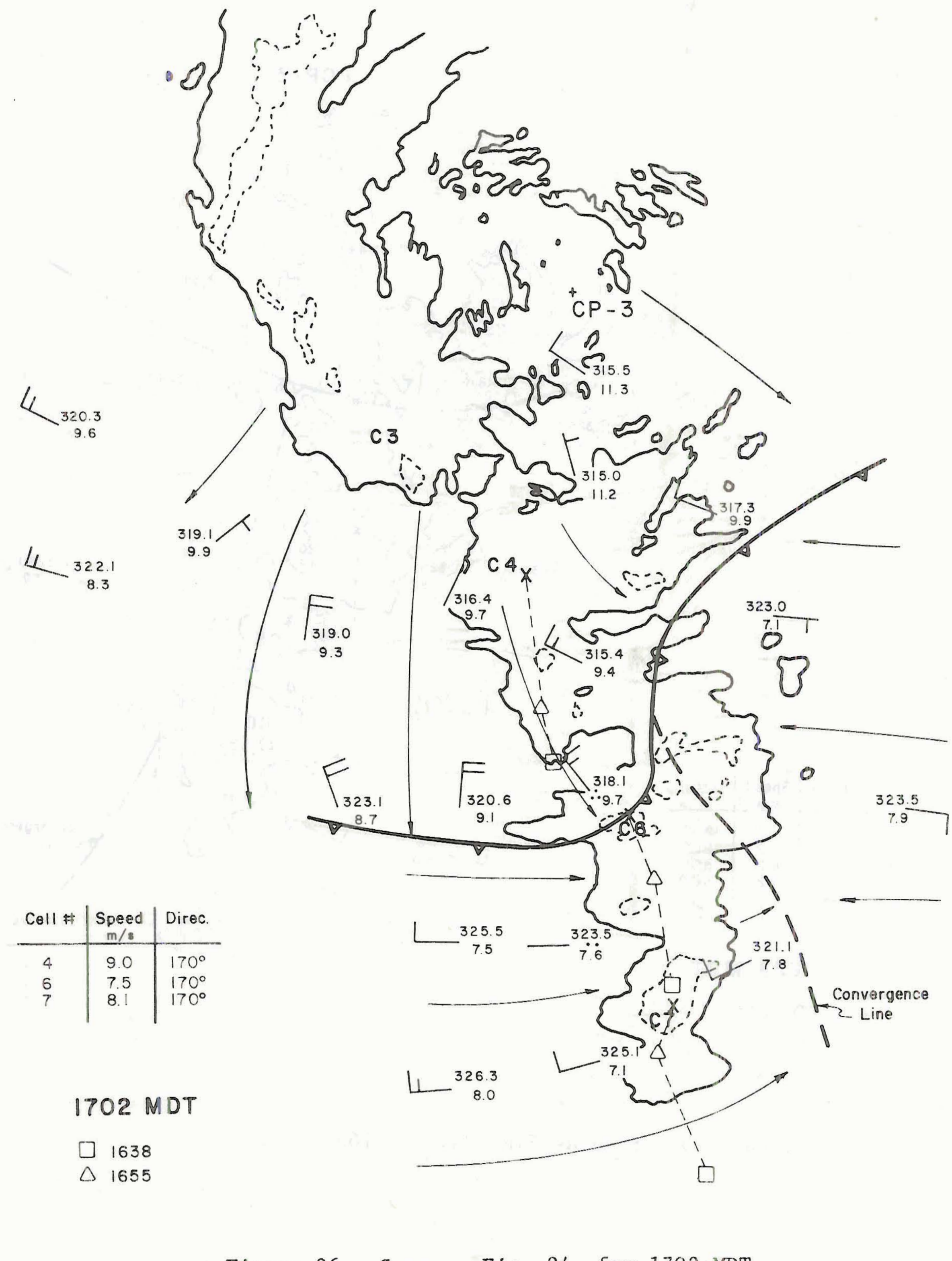


Figure 26. Same as Fig. 24, for 1702 MDT.

at a rate of over 100 mm hr^{-1} was measured near cell C6. Strong new cell development continued on the south end of the mesoscale line. A new line of intense convection had formed in the Blue River area, outside of South Park to the northwest.

The rapid southward movement of the cold front continued through 1720 MDT (Fig. 27). Surface air in the northerly wind region was much colder and wetter under the mesoscale line of storms than in the western part of South Park. Here, the post-frontal air had the same θ and q_v ($\sim 320^oK$, 9 gm kg^{-1}) as the westerly air which continued to advect across the ridge-top stations. In northeastern South Park, winds had shifted to strong westerlies in cold downdraft air. As the meso-cold front passed over all of the PAM stations at 1742 MDT (Fig. 28), it gave the appearance of being radial surface outflow, centered on the northern end of the mesoscale line. Once again, the strongest echo development had occurred near the frontal location (cell C9).

The mesoscale convective activity which existed in South Park at 1742 MDT was organized into a coherent cell line. This line was at least 70 km long and 10-15 km wide, consisting of at least five major convective elements (cells). The cell line was oriented roughly parallel to the upper wind direction. Cells were moving downwind along the line at 5-10 ms^{-1}, while new growth was occurring at the southern end, tending to maintain a constant position for the line as a whole. The location of maximum cell intensity, initially in the north end, had shifted to the south end, roughly coinciding with the passage of a meso-cold front with northerly winds.

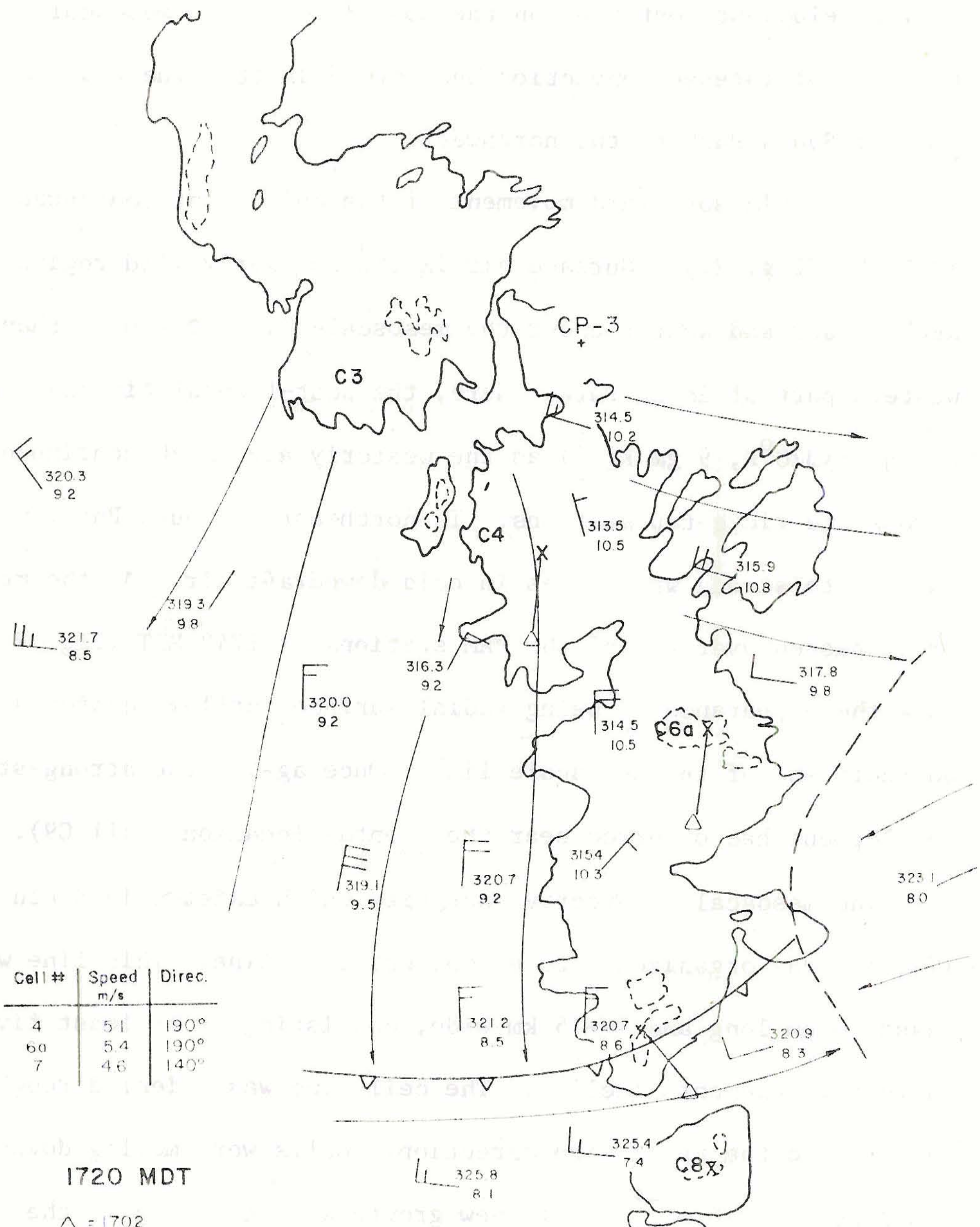
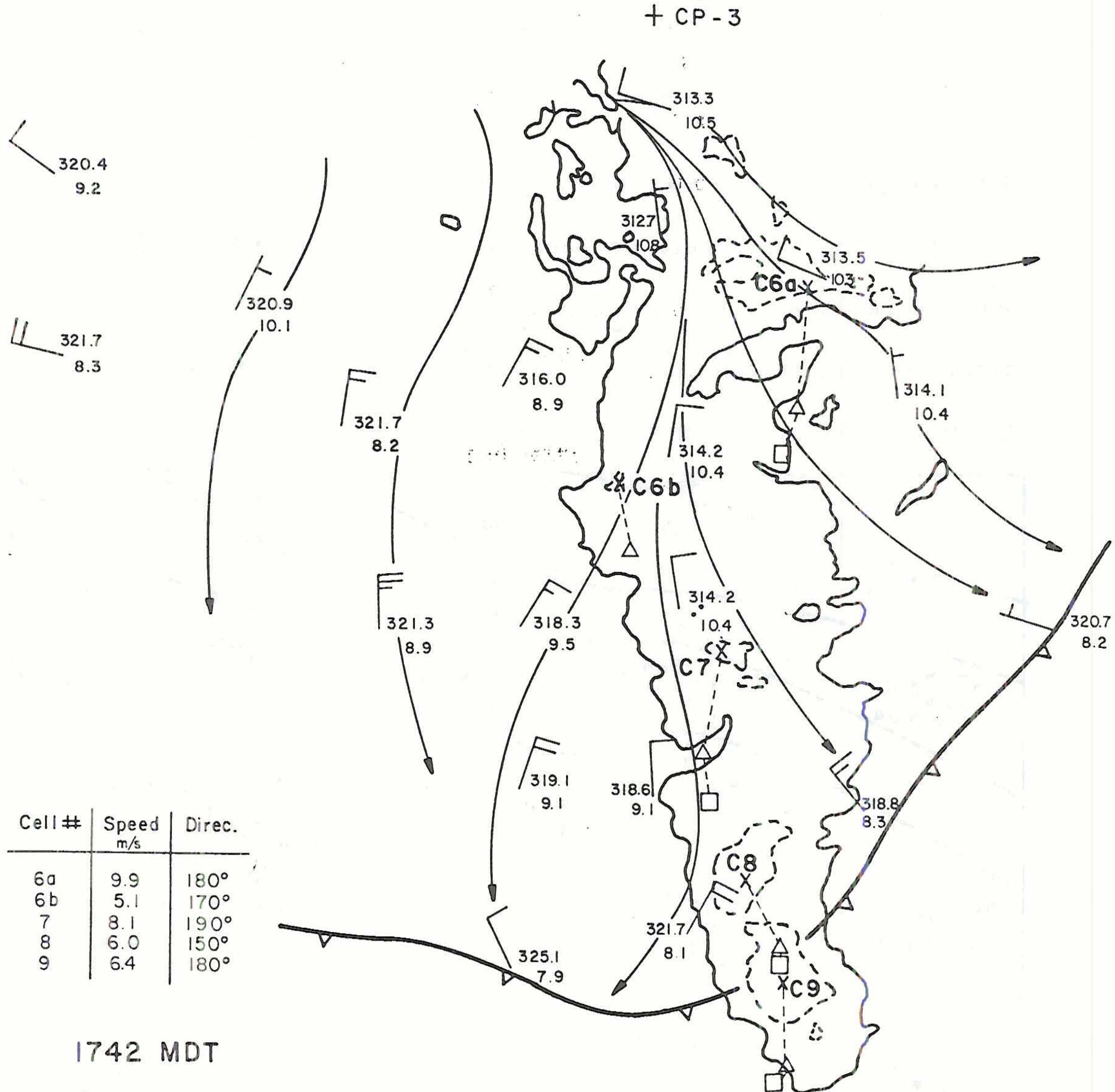


Figure 27. Same as Fig. 24, 1720 MDT.



Cell #	Speed m/s	Direc.
6a	9.9	180°
6b	5.1	170°
7	8.1	190°
8	6.0	150°
9	6.4	180°

1742 MDT

△ 1730

□ 1720

Figure 28. Same as Fig. 24, for 1742 MDT.

The intrusion of energetic northerly surface winds into South Park was apparently not a locally generated phenomenon. In the next section, an attempt is made to determine the causes of the intrusion, using synoptic and large-mesoscale data. Then, the South Park scale is resumed and the more complex cell-environment interactions which occurred after 1742 MDT are documented.

3.6 19 July 1977 - 1800 MDT Larger-Scale Observations

The complex pattern of surface flow and convective activity in South Park late in the afternoon of July 19 can be better understood after looking at the larger scale data from 1800 MDT (0000 GMT, 20 July). At 500 mb (Fig. 29), the subtropical high pressure, centered over

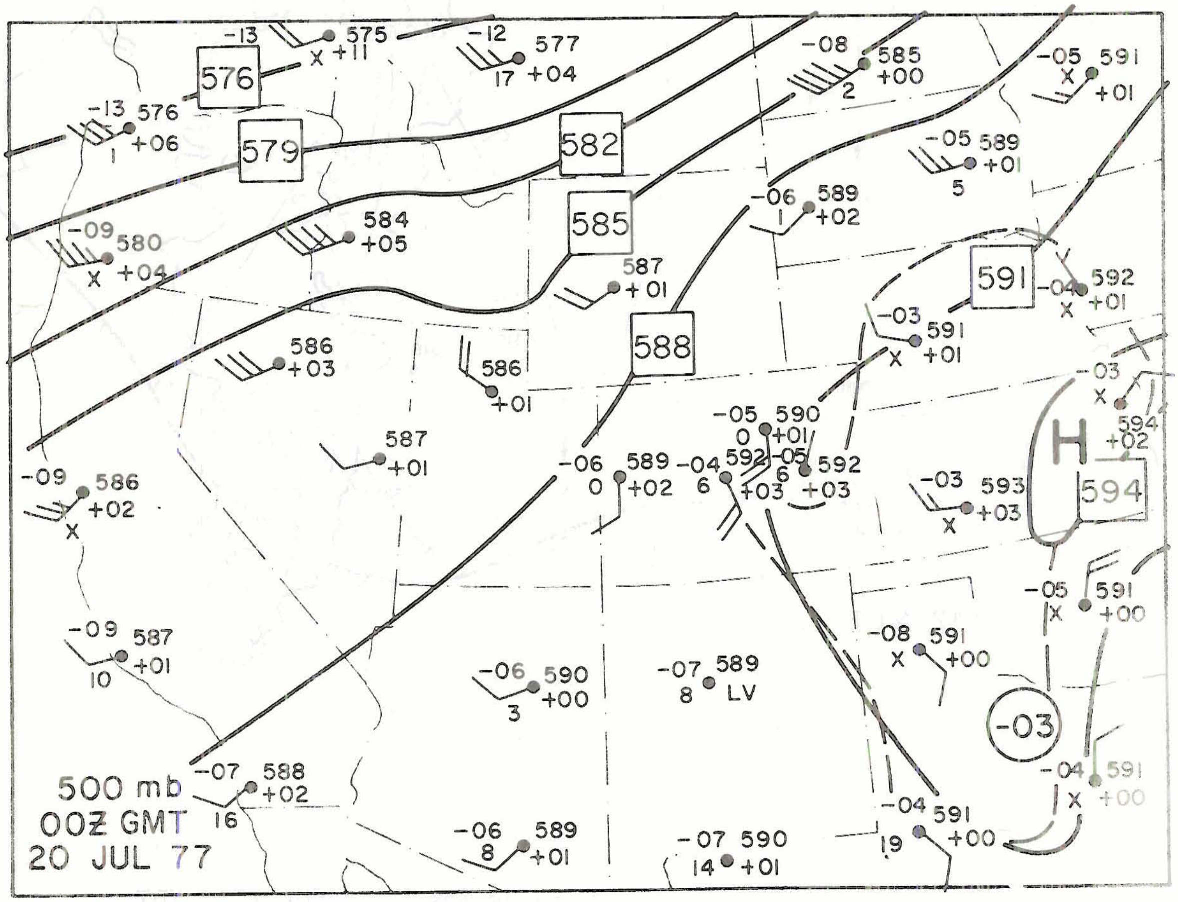


Figure 29. Same as Fig. 13, for 1800 MDT, 19 July, 1977 (0000 GMT, 20 July, 1977).

eastern Kansas, had built westward during the day to cover all of Colorado with basically south winds. Winds at Grand Junction, which had been 260° in the morning, had shifted back to 190°. A weak short-wave in northern Utah helped increase convergence into the area of northern Colorado and southern Wyoming. 500 mb dewpoints were high as far east as Limon, as well as in a band extending northeastward into Canada.

The location and extent of the strongest convective activity can be seen on a satellite infrared (IR) image (Fig. 30) taken at 1800 MDT. Very cold cloud areas, associated with deep thunderstorms, formed three bands extending roughly north to south. The easternmost band extended from South Park to southeastern Wyoming, with the highest clouds at the southern end in South Park. The center of this line bulged toward the east, well out into the plains, as confirmed by the Limon radar summary for 1830 MDT (Fig. 31) (note - these summaries do not cover Wyoming or west of the Rockies). Note that, except for a few weak echo areas in southern Colorado, convective rainfall was restricted to an area north and west of the solid arc in Fig. 31. This is consistent with the IR image in Fig. 30.

The surface weather map (Fig. 32) for 1800 MDT indicates the probable extent of the region of northerly flow which intruded into South Park starting at 1600 MDT. This region extended from south of the PAM network northward into Wyoming. The stations with north winds also had overcast skies, falling temperatures, and rapidly rising surface pressures. South and east of the line of convective echoes (marked

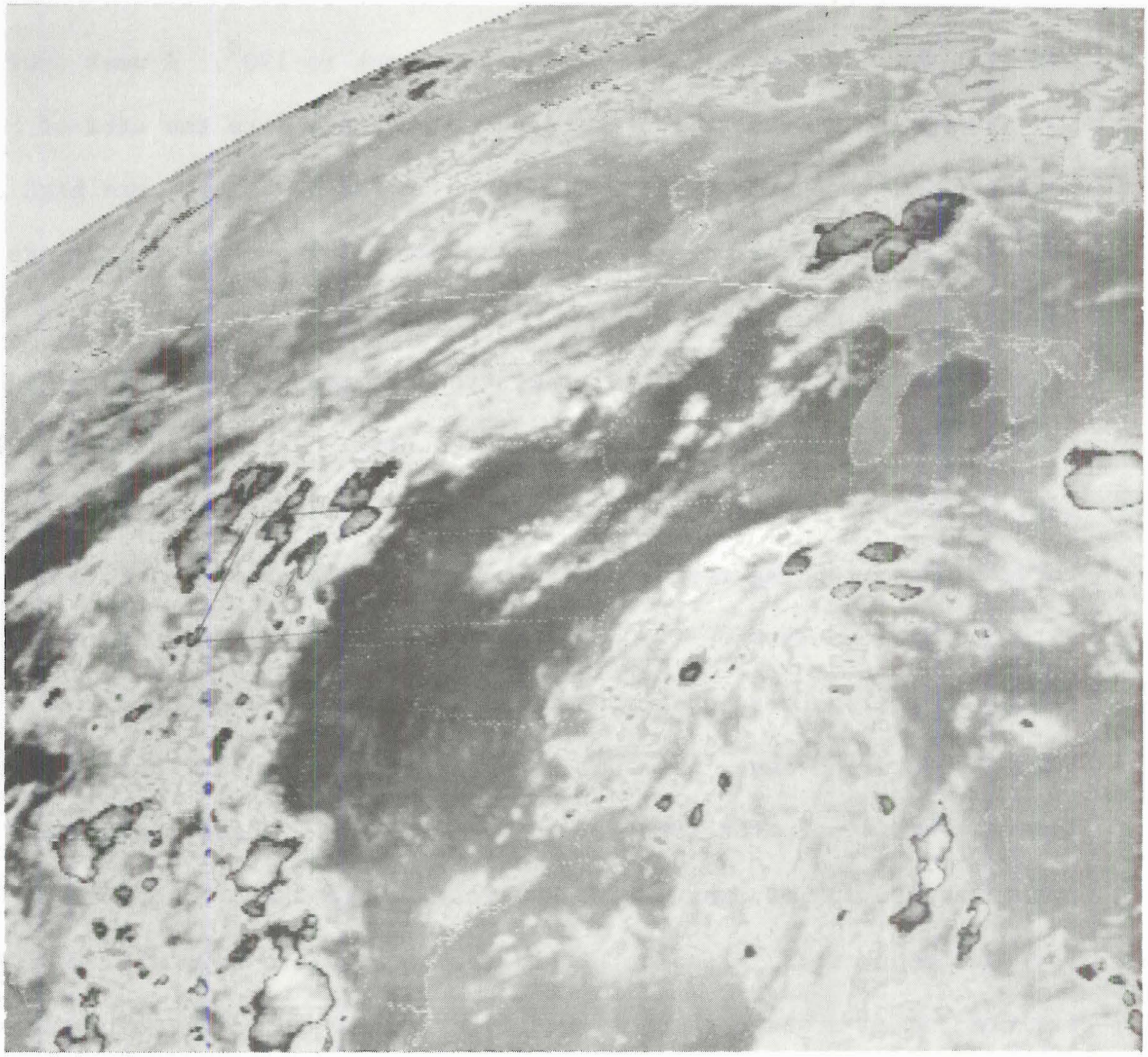


Figure 30. Same as Fig. 15, for 1800 MDT, 19 July, 1977.

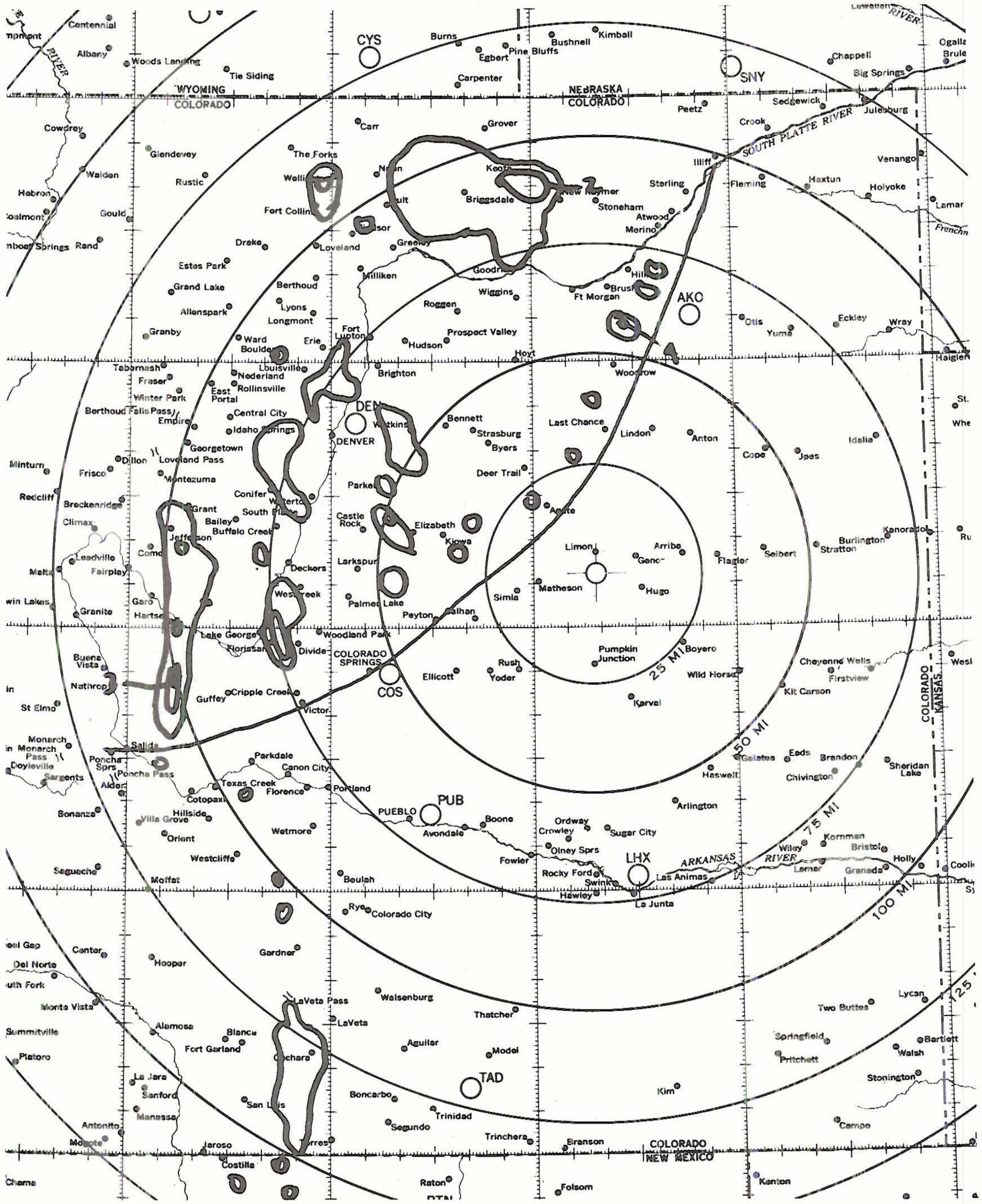


Figure 31. Limon radar summary for 1830 MDT, 19 July, 1977. Dark contours are radar echoes, with contour levels as in Table 1. Concentric circles are range from Limon in 46 km increments.

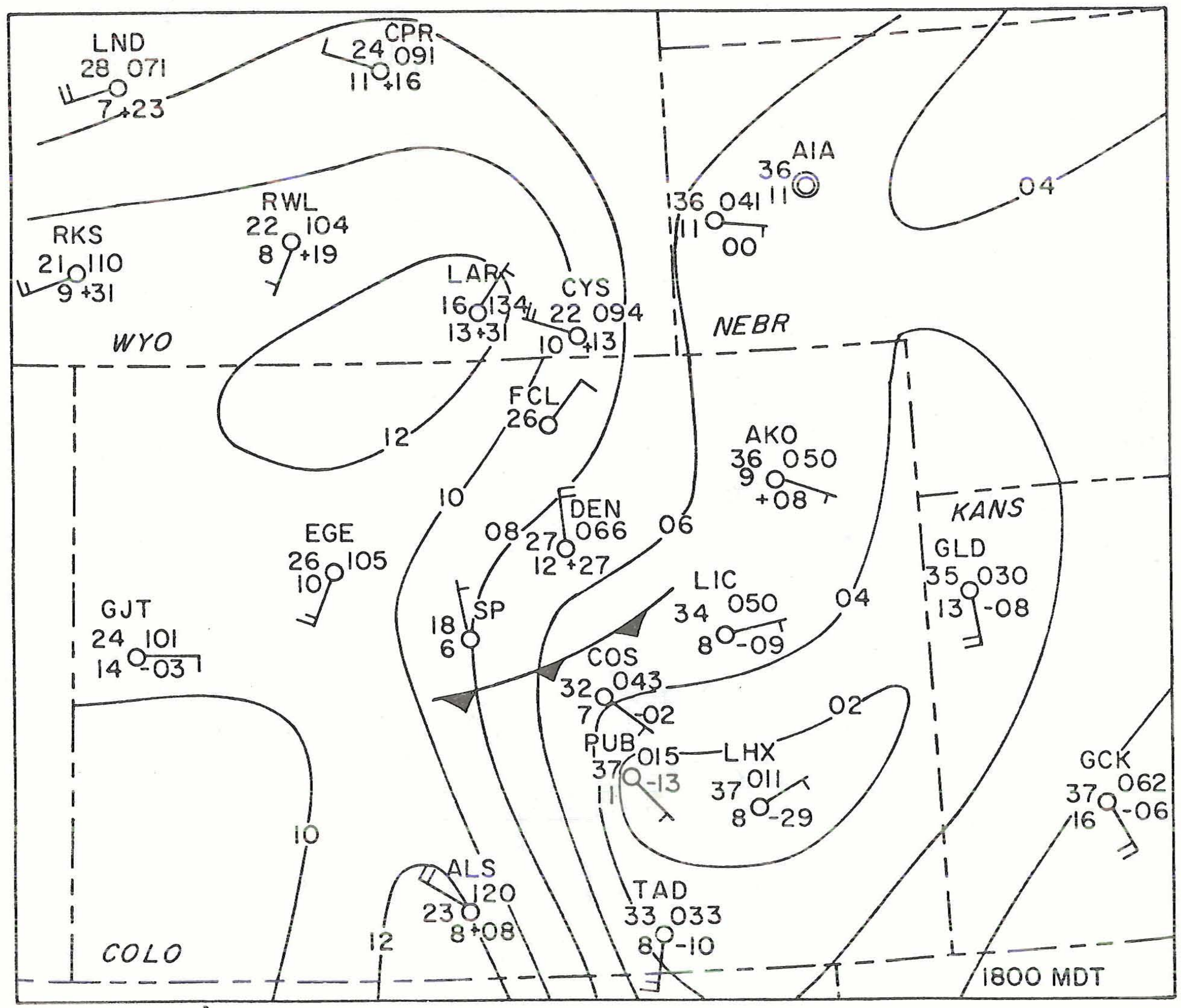


Figure 32. Mesoscale surface map, like Fig. 14, for 1800 MDT, 19 July, 1977.

with a cold front symbol in Fig. 32) pressures continued to fall with strong heating under clear to partly cloudy skies. Winds were light easterlies and southeasterlies.

The boundary of convective activity visible on radar and satellite images (Figs. 30 and 31) probably marked the easternmost advance of moist Pacific air in the planetary boundary layer. Surface data (NWS) from 1500-2200 MDT indicate that the first occurrence of strong thunderstorms east of the Rockies was at Cheyenne, Wyo. (CYS on Fig. 32) at about 1500 MDT. At this time, Cheyenne winds shifted to northerly, and the temperature dropped about 10^{o}C. This phenomenon then occurred sequentially at each station farther south along the Front Range in the manner of a synoptic-scale cold front. By 1800 MDT, the boundary of this wind shift had passed south of Denver and South Park, as indicated in Fig. 32. The Denver rawinsonde for this time showed a layer of north-northeasterly winds extending from the surface (840 mb) to above 700 mb, or about 1.5-2.0 km above ground level. Wind velocities decreased with height, then switched to light southerly winds at the top of this layer. This layer had a uniform potential temperature of 321^{o}K, with an average mixing ratio of 7.5 gm kg^{-1}. A simultaneous sounding from Limon (LIC) revealed a very warm ($\theta=324^{o}$K), deep (at least 3.5 km) boundary layer, with very light winds extending to the 400 mb level.

Earlier in the day, at 1333 MDT, South Park radar and PAM data (Fig. 22) had shown that the mountain barrier extending to about the 650 mb level (or 3.5 km MSL), northwest of the Park, had been sufficient to block the rapid horizontal advection of very moist Pacific air into the Park. This moisture had created deep thunderstorm activity just outside South Park, yet the onset of deep storms in South Park was delayed for about three more hours. In southern Wyoming, however, a gap in the Rocky Mountain barrier about 2.5 km above MSL (750 mb) allowed low-level moisture advection to proceed more rapidly into the Cheyenne area.

The strong thunderstorm activity observed just north of South Park early in the afternoon extended northward along the Front Range into Wyoming. Low-level air in these mountains was cooled by a combination of thermal advection from the west, thunderstorm downdrafts chilled by evaporating precipitation and lack of surface heating due to cloudiness. To the east, extreme surface heating continued in the cloud-free plains. This contrast produced a strong east-to-west surface pressure gradient which lasted throughout the day. After 1500 MDT, deep thunderstorm activity invaded the plains, beginning in the Cheyenne area. Rapidly rising surface pressure under these storms helped rotate the strong pressure gradient around to a southeast-northwest orientation, as shown on Fig. 32. The low-level thermal contrast observed between the Denver and Limon soundings emphasizes the thermal nature of the northerly surface winds. It seems probable that the northerly winds were able to propagate southward in a manner similar to the "density current" described in section 2.3. Thus, as the cool outflow from a number of large cells pushed southward, it created a better environment for more large cells to form (i.e., convergence, increased moisture, stronger wind shear), thus creating more cool outflow from the new cells. The location of new cell growth at the southern end of the thunderstorm line in South Park is consistent with the density current concept.

3.7 19 July 1977 - Evening Post-Frontal Thunderstorm Activity

In the two previous sections, the occurrence of a mesoscale line of thunderstorms in South Park on 19 July 1977, and the development of a coherent region of northerly surface flow have been described. Factors related to the occurrence of this northerly flow which are driven by a large-mesoscale mountain-plains contrast were shown. In this section, the thunderstorm cell environment which existed in South Park late in the afternoon will be described in more detail. Then, the interesting variety of cell motions and interactions which occurred in this environment will be documented. Included among these are cell splitting, simultaneous right-and-left-moving storms, and a quasi-steady-state supercell.

The South Park sounding taken at 1710 MDT on July 19 is plotted in Fig. 33. Two major uncertainties exist in the data for this sounding. The first problem was the lack of an adequate baseline calibration. This may have created an absolute error in all values of both temperature and humidity. However, the relative features of the temperature and humidity plots are physically meaningful, and the estimated baseline is not grossly in error. The second problem was the lack of wind data between the surface and 500 mb. These winds have been estimated from visual observations of the balloon trajectory and corroborating data (such as winds from the ridge-top PAM stations). Wind data at 500 mb and higher are valid.

The sounding in Fig. 33 reveals a strong subsidence inversion at 490 mb, probably generated within South Park by storm-scale subsidence. Below this level, the moist PBL was stratified into three fairly

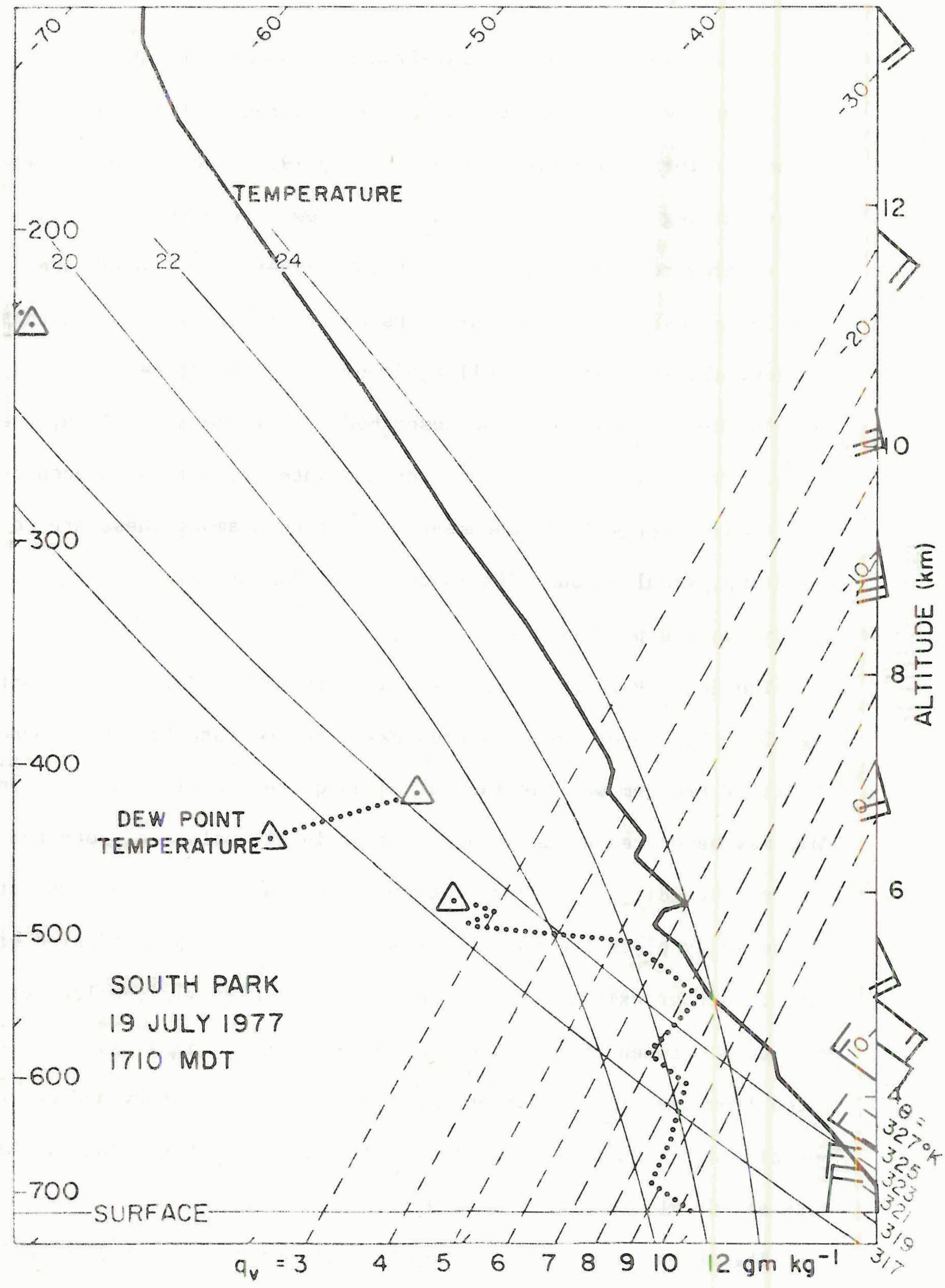
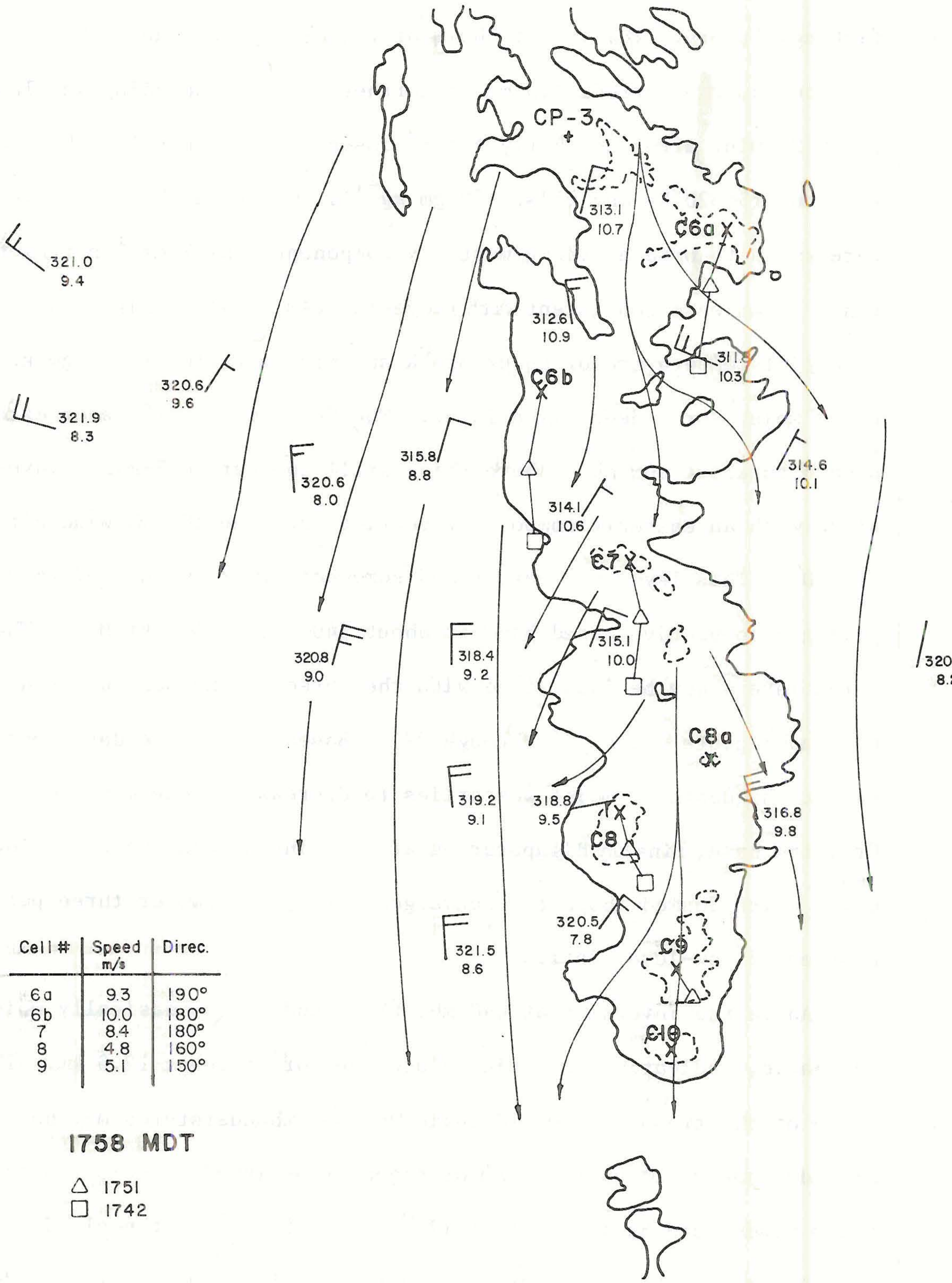


Figure 33. South Park sounding of 1710 MDT, 19 July 1977, plotted on skew-T log-P diagram. Winds between the surface (720 mb) and 500 mb are estimated.

distinct layers. The lowest 300 m of the atmosphere, up to 690 mb, was the layer of strong (10 ms^{-1}) northerly winds (sounding was launched about 25 min. after northerly front passed the base site). This layer was cool (θ=320^{o}K) and moist (10 gm kg^{-1}). Winds in the next layer were known to have a strong westerly component (the 7 ms^{-1} northwesterly winds shown were consistent with ridge-top PAM data). This layer had a potential temperature of about 323^{o}K and mixing ratio of 8.5 gm kg^{-1}, quite moist for a deep mixed layer. The "northwesterly" layer extended upward to about 600 mb. Above this, still another well-mixed layer had winds with an easterly component, veering into the 500 mb wind direction of 170^{o}. This layer was warmer and somewhat drier, with q_v=7 gm kg^{-1} giving a convective cloud base at about 540 mb, or 5.0 km MSL. These three layers may be identified with the three air masses observed on PAM-radar plots (Figs. 24 through 27). Based on surface data, one might expect the depth of moist westerlies to decrease as one moves eastward from the base, finally disappearing at the line of convergence. Thus, cells which formed above the convergence line had two or three potential sources of low-level inflow.

Above the inversion at 490 mb, the sounding was basically moist adiabatic, indicating potential cloud tops of at least 12.0 km. The shape of the tropopause would indicate that thunderstorms may have already penetrated up to 14 km or higher (confirmed by CP-3 radar). Upper winds were basically from 170^{o} at 10-15 ms^{-1} in the cloud layer.

After 1742 MDT (Fig. 28) the character of the mesoscale thunderstorm line and its associated surface winds began to change. Wind directions under the line of cells became much more variable. By



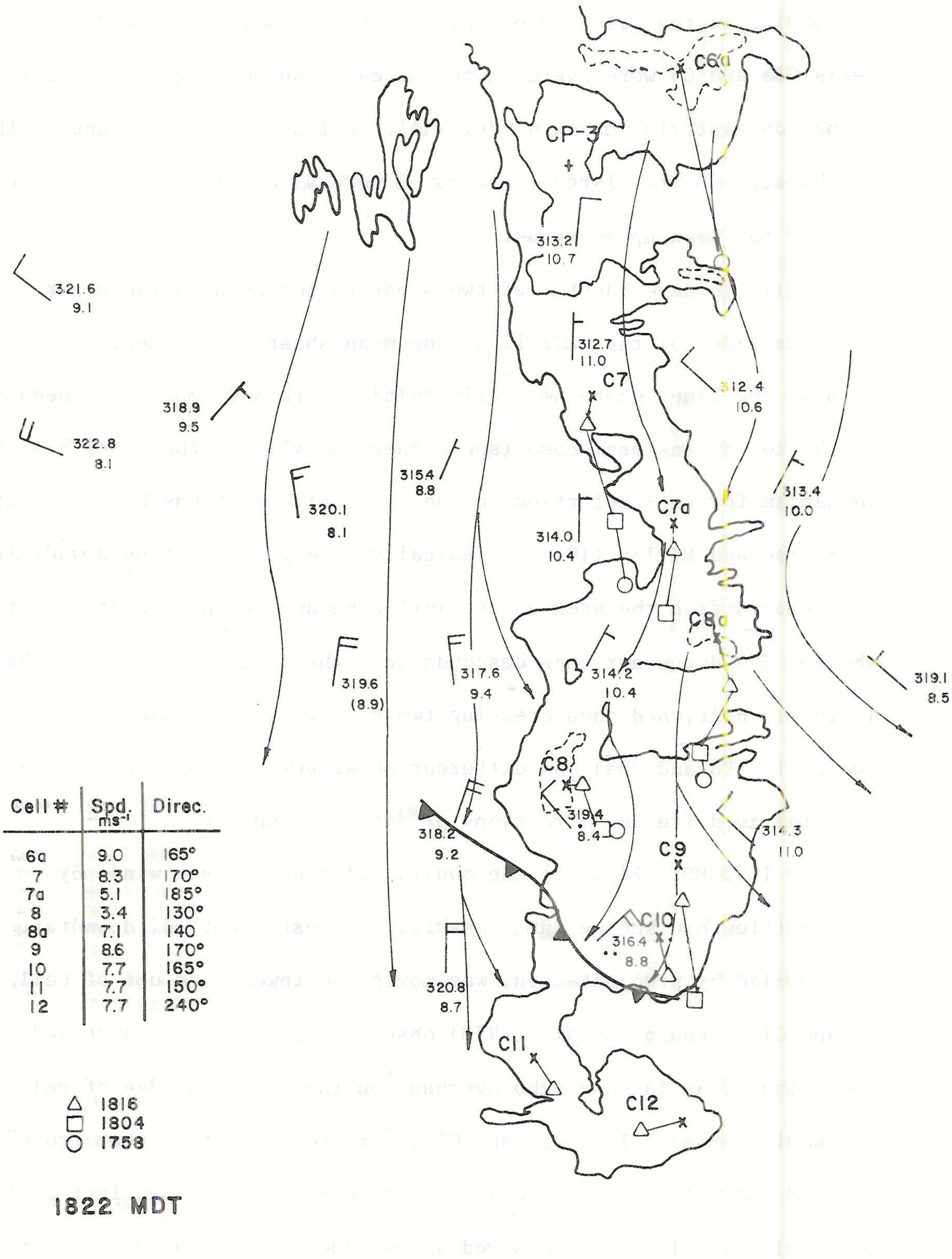
Cell #	Speed m/s	Direc.
6a	9.3	190°
6b	10.0	180°
7	8.4	180°
8	4.8	160°
9	5.1	150°

Figure 34. Same as Fig. 24, for 1758 MDT.

1758 MDT (Fig. 34) a new cell, called C8a, had split off from the northeast side of cell C8. Knupp, et al. (1978) presented a very detailed discussion of the life history of cell C8, as well as C2 and C11. Cells C8a and C9 were overhung to the east, suggesting continued reliance on easterly inflow winds, while cell C8 became overhung to the northwest. C8 grew larger, and moved more slowly in a direction to the left of the mean upper winds.

While we have identified two separate inflow directions for opposite sides of the cell line, the mean shear environment near the axis of the line, where new cells initially formed, must have been close to the two-dimensional case (speed shear only) described earlier. A mechanism for cell splitting in such an environment has been suggested by Thorpe and Miller (1978). Basically, the precipitating downdraft is not removed from the area of the inflow because of a lack of directional shear. The downdraft then descends into the inflow region, cutting the inflow in half, and thus creating two cells. In our case study, the two cells (C8 and C8a) had different shear environments, and hence traveled in different directions at different speeds.

By 1822 MDT (Fig. 35) the modification of surface winds by cell outflow had become unmistakable. A "gust front" of downdraft air, accompanied by precipitation, was moving southwestward out of cells C8 and C10. Knupp, et al. (1978) observed the rapid collapse and surfacing of an intense echo overhang on the southern edge of cell C10. Two newly formed cells, C11 and C12, were south of the "gust front". Cell C8 had been moving slowly in a direction well to the left of the upper winds, while C8a had moved almost due north at a much faster rate. This created a gap in the line about 10 km wide.



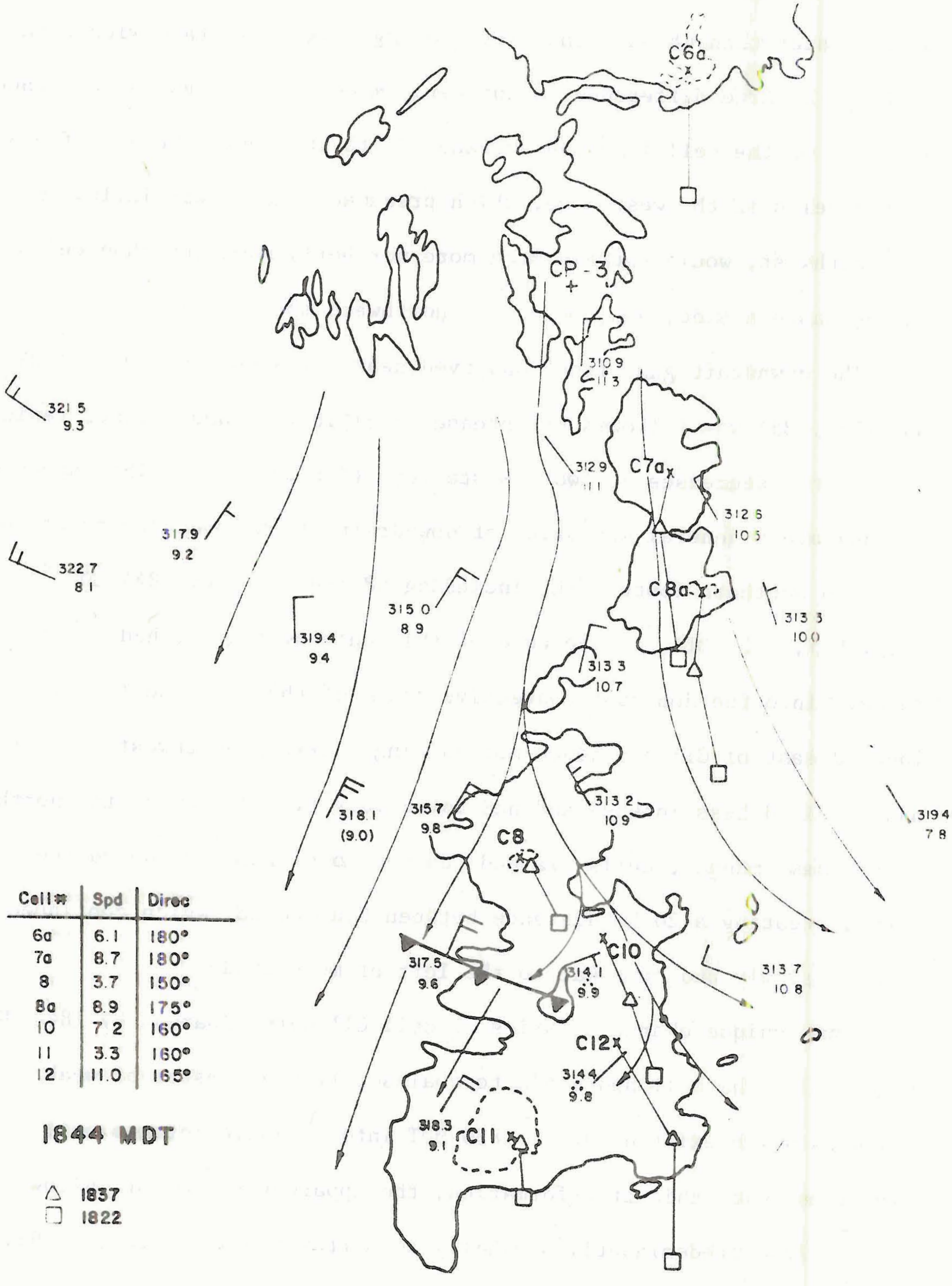
Cell #	Spd. ms^{-1}	Direc.
6a	9.0	165°
7	8.3	170°
7a	5.1	185°
8	3.4	130°
8a	7.1	140
9	8.6	170°
10	7.7	165°
11	7.7	150°
12	7.7	240°

Figure 35. Same as Fig. 24, for 1822 MDT.

Cell C8a, which moved to the right of mean winds, consistently moved faster than C8 and other left-moving cells. Surface wind data indicate a large difference in northerly momentum between the air under and east of the cell line and surface air to the west. Thus, left-moving cells on the west edge, which presumably get their inflow from the northwest, would entrain much more northerly momentum than cells on the eastern side, and would move northward more slowly.

The downdraft gust front observed near cells C8 and C10 at 1822 MDT (Fig. 35) was followed by intense precipitation and further rapid temperature decreases at two PAM stations (#16 and #27). This appeared to indicate a general surfacing of downdrafts from several convective cells in southern South Park, including C8 and C10. By 1844 MDT (Fig. 36), cell C11, at the edge of this outflow region, had grown rapidly into the dominant convective storm of the day. Cell C12, located east of C11 and hence not gaining a strong northwesterly inflow, had remained less intense and had moved very rapidly toward the north. In the same manner, cells C7a and C8a had moved rapidly toward the north, creating a 20 km distance between C8a and C8, which continued to move slowly and somewhat to the left of mean winds.

Some unique characteristics of cell C11 were apparent by 1844 MDT (Fig. 36). The cell had begun to coalesce from a cluster of weak updrafts which existed before 1830 MDT into a single intense cell. Coincident with this transformation, the apparent region of inflow changed from predominantly southerly to northwesterly (Knupp, 1979). A hook-shaped appendage had appeared on the southern edge of cell C11. This was found to contain a separate reflectivity core, emanating



Cell#	Spd	Direc
6a	6.1	180°
7a	8.7	180°
8	3.7	150°
8a	8.9	175°
10	7.2	160°
11	3.3	160°
12	11.0	165°

Figure 36. Same as Fig. 24, for 1844 MDT.

from the central core (Knupp, et al. 1978). Also coincident with the intensification of C11, surface northerly winds west of the mesoscale storm complex shifted 30 - 40^{o} to the east, such that the surface streamlines seemed to split and flow around the storm system (Fig. 36).

By 1856 MDT (Fig. 37), yet another new cell had split off from cell C8 and moved northward (cell C8b). All of the smaller cells had moved north relative to C11, and were at least 20 km away. Cell C11 had just passed over a surface station (#15), bringing substantial rainfall and very cold temperatures (θ=311^{o}K) in a strong easterly downdraft. The hooked region of C11 appeared to rotate in a cyclonic sense, and had its own 40 dBz maximum. Easterly winds within and east of cell C11 represent substantial modification of the mean flow by this storm.

A change in the dynamics of these storm systems occurred at about 1908 MDT. RHI scans indicate that storm inflow to C11 from the south ceased entirely, while inflow from the northwest continued. As the southern overhang collapsed, strong westerly outflow began near the location of the hook. Cell C11 began to move more toward the north, at 150^{o}. At the same time, cell C8 stopped moving entirely and began to dissipate, creating substantial surface precipitation. By 1922 MDT (Fig. 38), surface winds gave the appearance of strong cyclonic rotation about the cell location, creating a "col point" in the streamline analysis on the northeast side of the storm, where the prevailing northerlies were countered by cyclonic outflow from the storm. Generally, the strength and coherence of northerly flow had decreased between 1856 MDT and 1922 MDT.

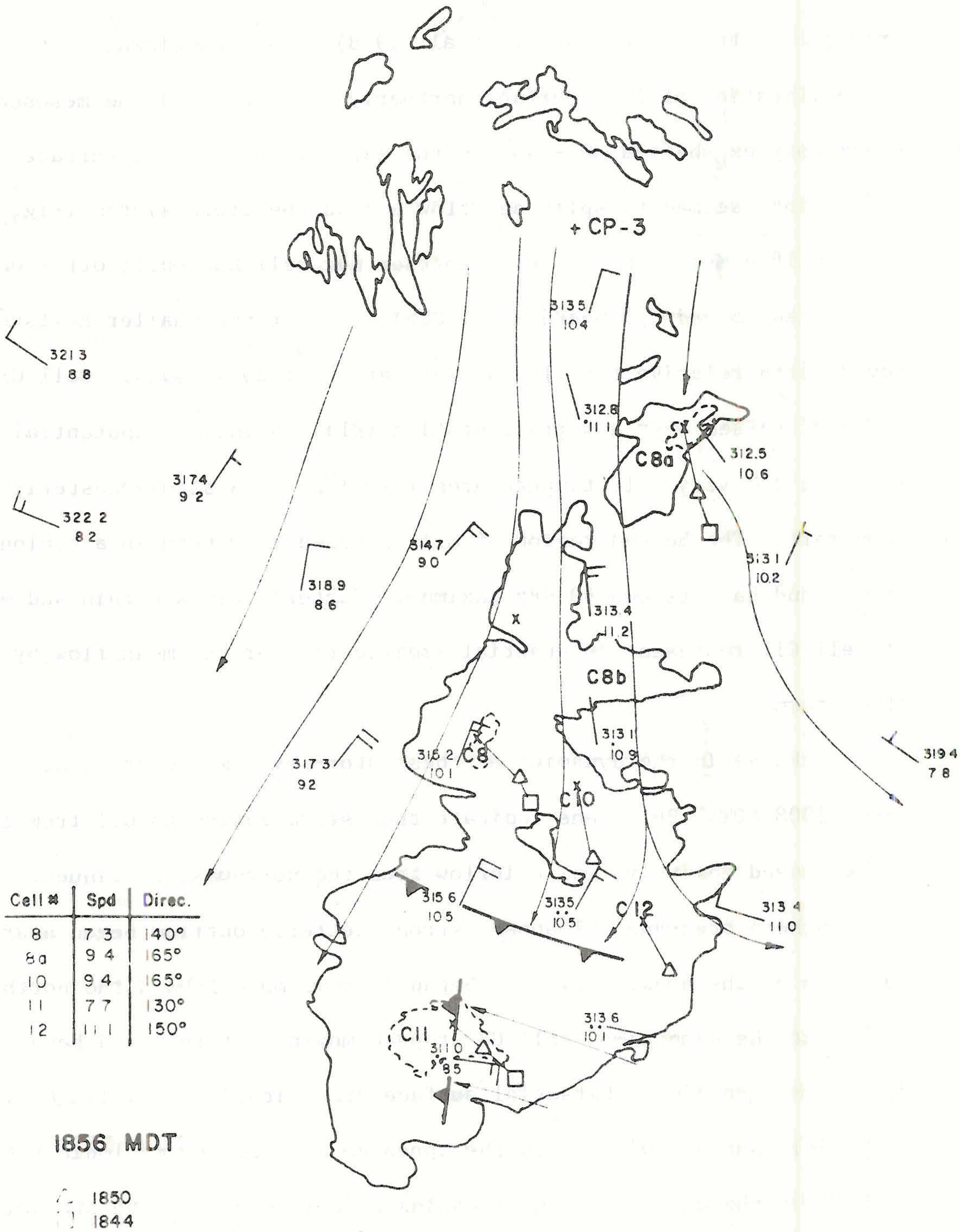


Figure 37. Same as Fig. 24, for 1856 MDT.

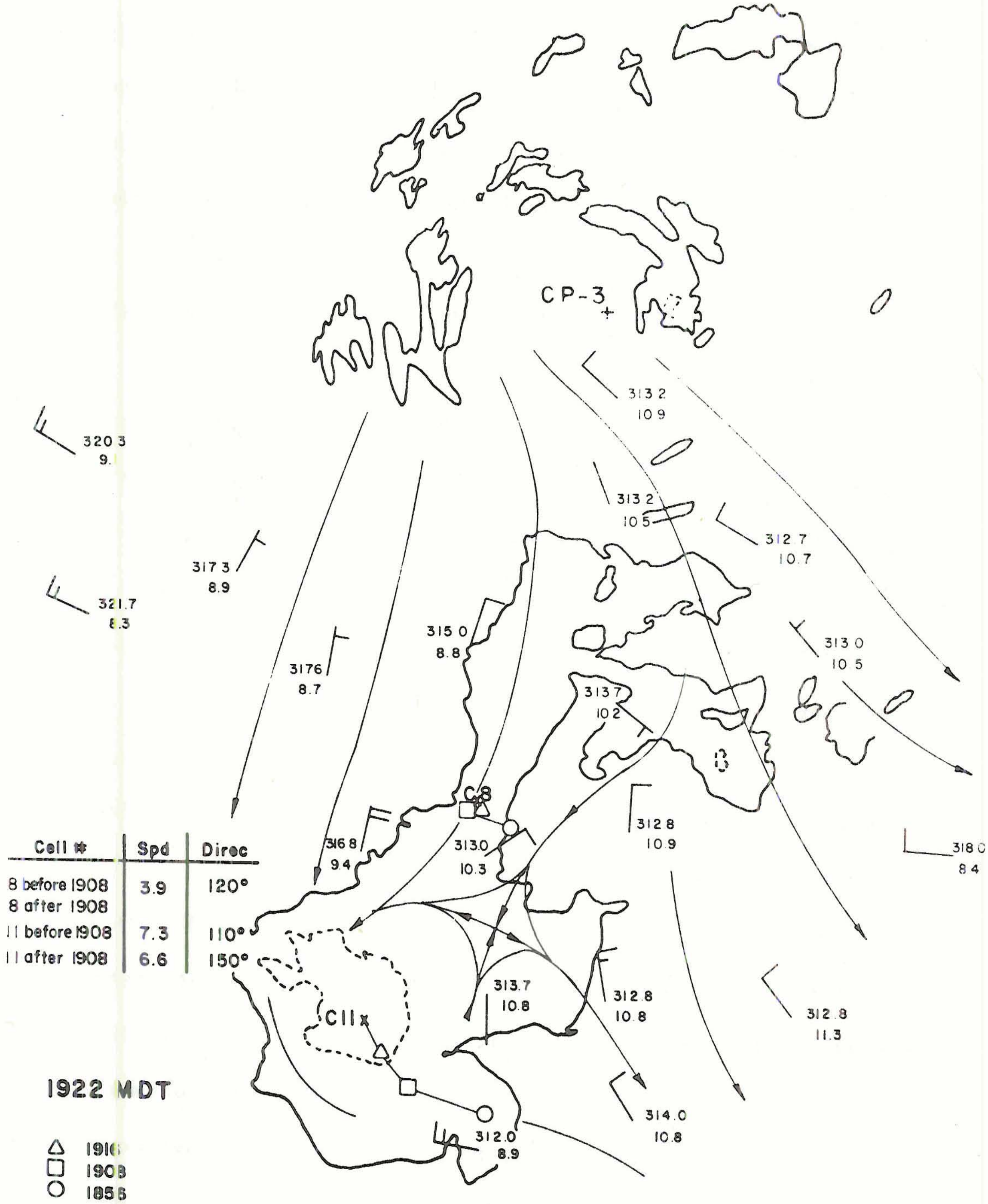


Figure 38. Same as Fig. 24, for 1922 MDT.

Another dynamic change occurred in cell C11 at 1928 MDT, when it developed a secondary reflectivity maximum in the overhanging northwestern part of the echo. As the trailing echo decreased in intensity, the cell then appeared to be moving by a process of discrete rather than continuous propagation. Thus, by 1939 MDT (Fig. 39), cell C11 seemed to have moved at 10 ms^{-1} toward the northwest. Winds in most of South Park had become lighter (5 ms^{-1} or less) and more variable in very cold, moist air. Some moderate convective activity was occurring in a ring around this pool of cold outflow.

After 1939 MDT, cell C11 moved over the high mountains of the Mosquito Range. Although the CP-3 radar ceased data collection after 1952 MDT, PAM data indicate the probable course of events. At 2010 MDT, a cold gust front passed over stations #17 (base) and #8. At 2015 MDT, station #6 (Horseshoe Peak) reported intense rainfall for a short time. Since the mountain top was within the cloud, however, very little change occurred in θ or q_v as the storm went by. The ridge tops continued to have strong northwesterly winds, while the rest of South Park had light and variable winds after 2100 MDT.

Total precipitation data for the time period 1600-2400 MDT are contoured in Fig. 40. The maximum at the northernmost station (#28) occurred shortly after 1600 MDT, and came from cell C2. The amount may actually have been greater than 21.0 mm, but the PAM data are missing for part of this storm. The high amount at the southernmost station (#15) came from C11 at about 1856 MDT. Except for these two cases, most of the precipitation which fell seemed to be associated with dissipating radar echoes. Specifically, the 22 mm rainfall at station

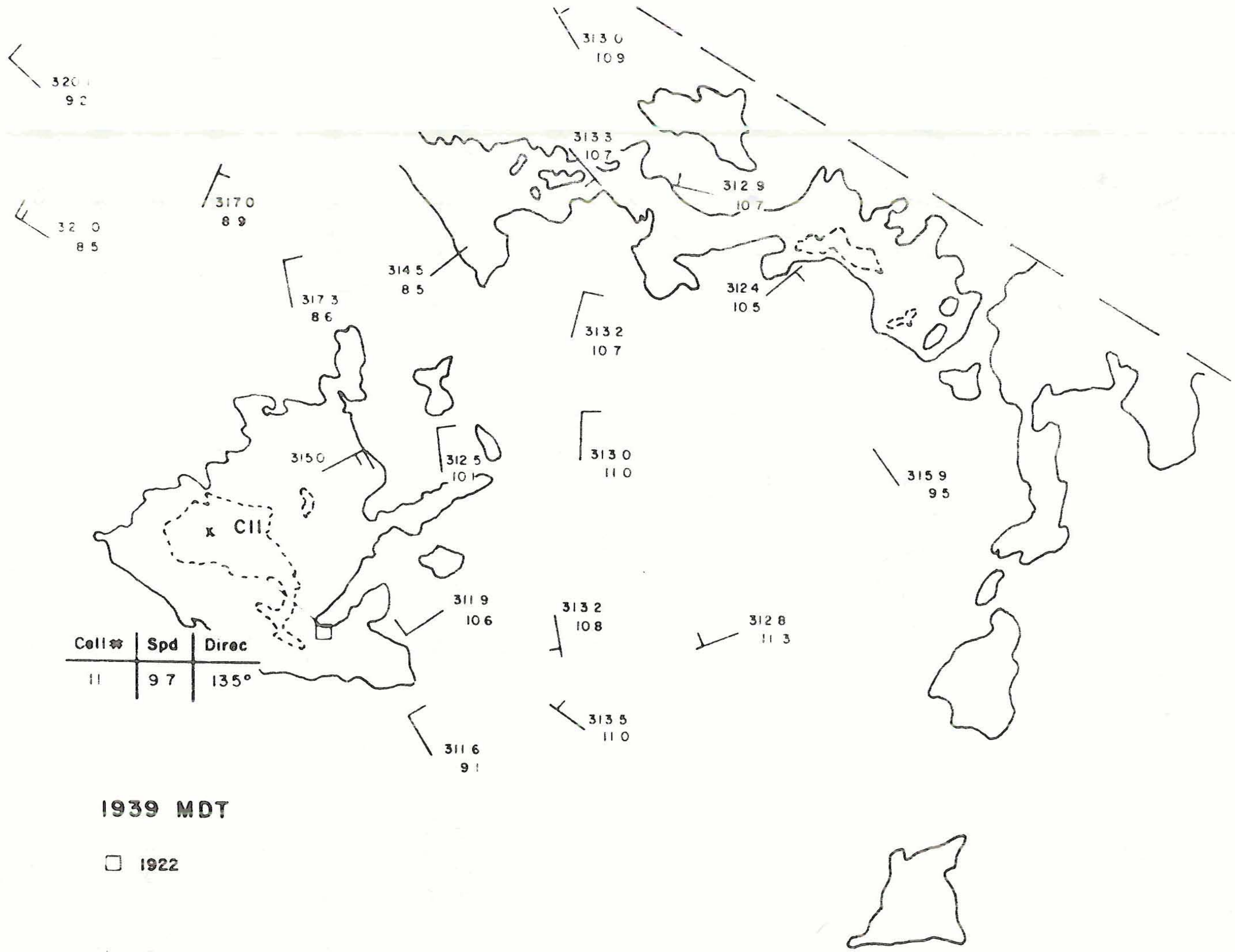


Figure 39. Same as Fig. 24, for 1939 MDT.

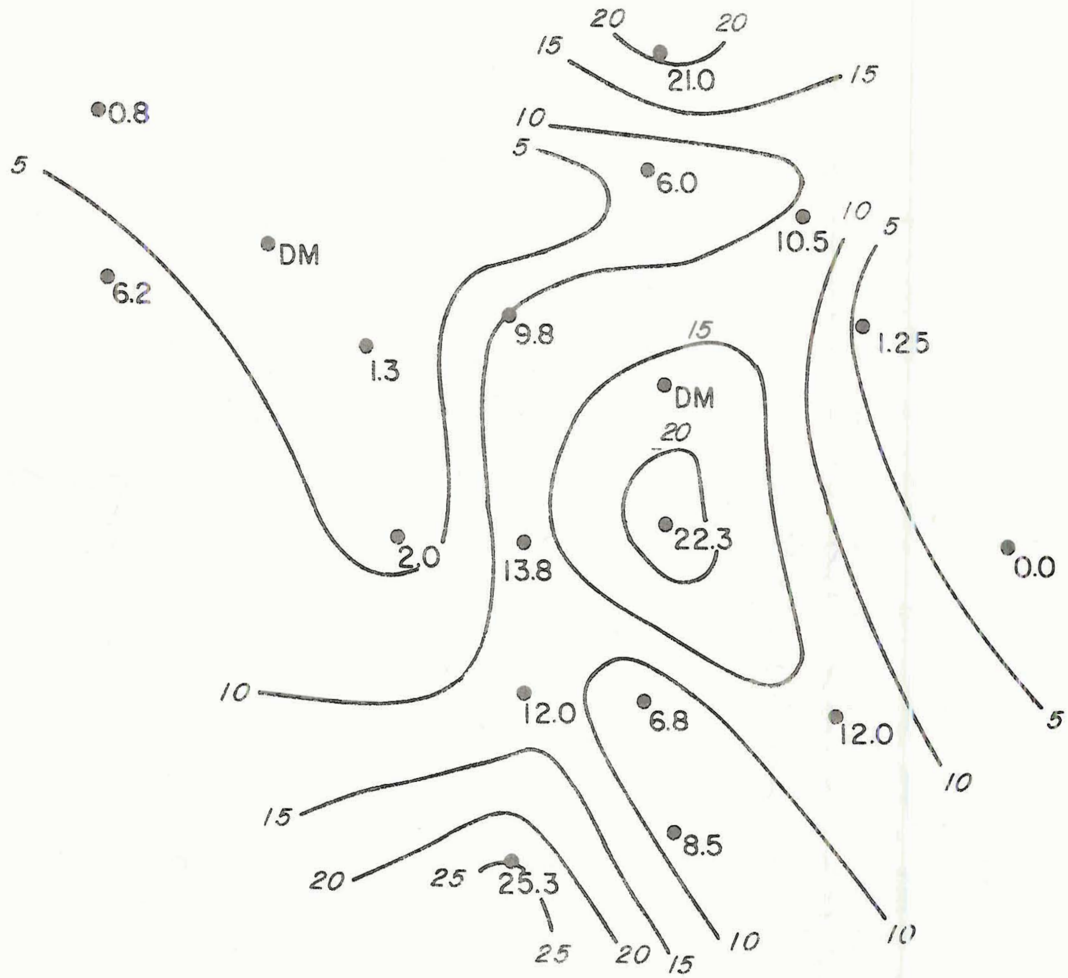


Figure 40. Total rainfall in mm observed at PAM stations, for the time period 1600-2400 MDT, 19 July 1977. Contour interval 5 mm.

#9 seems to have come from cell C6, which was relatively weak and short-lived, but did spawn two cells.

Radar and satellite data indicate that most of the Front Range areas were covered with clouds and light precipitation for much of the night. From Denver toward the northeast, several large, slow-moving cells were active until after 0230 MDT, July 20. A few large, isolated supercells were present in eastern Wyoming at this time.

3.8 19 July 1977 - Summary

July 19, 1977 was the first of a series of days of high precipitation and severe weather in South Park. July 19 was characterized by intense, long-lived convective storms which moved slowly northward within South Park. The moisture mecessary to support this convection was provided by a synoptic scale upper level southerly flow pattern (sometimes called "monsoonal" flow). A complex surface flow pattern was apparently driven mainly by large-mesoscale terrain-induced pressure and temperature gradients, interacting with synoptically driven flow from across the Rocky Mountains. Initial convection and some cell-environment interactions occurred on smaller scales, created within South Park. Some of the scales of motion reviewed in chapter 2, such as the morning valley wind, were obscured by larger scale forcing.

A brief time sequence of events, with their probable causes, may help clarify the roles which various scales and types of motion played on July 19.

As the day began, the subtropical high at 500 mb east of Colorado created strong subsidence east of the Rockies, while providing the southerly winds which imported Pacific moisture in a band extending through western Colorado into eastern Wyoming. In eastern Colorado, a thermal trough resulting from days of intense surface heating without moist convective release helped create an east-to-west surface pressure gradient which produced a basic northerly wind direction in the Front Range area. This gradient acted in a more direct manner throughout the day to create low-level westerly and northwesterly forcing of moist Pacific air across the mountains and into South Park.

After sunrise, strong surface heating in the plains and in South Park created a warm, deep dry convective PBL. Early deep moist convection in the mountains northwest of South Park helped maintain the pressure gradient which pushed the moist westerlies into South Park. Although initial moist convection in South Park did occur by 1230 MDT over certain terrain-favored convective locations ("hot spots"), most of South Park remained cloud free until about 1530 MDT. By this time, easterly slope winds from the plains had entered South Park, thus indicating that the elevated, strongly heated park had created a mesothermal low pressure center. South Park was thus a maximum area of low-level convergence and convective instability (as substantial Pacific moisture advected from the west).

Around 1530 MDT, a line of convective cells began to organize over a north-south line of low-level convergence in the center of South Park. At about the same time, strong, cool northerly winds invaded the Park from the north. This flow was apparently driven by an increasing contrast between the clouded, rainy mountains and the dry, heated plains, combined with a direct south-to-north pressure gradient created by outflow from some large convective cells which formed on the plains east of the Front Range. The passage of this northerly front through South Park enhanced the intensity of convection by creating low-level convergence, added moisture, and increased wind shear in the storm environment.

After the passage of the northerly cold front, the convective cells in the quasi-stationary mesoscale convective line began to exhibit more individualized interactions with their environment. Cells moved both left and right of the mean wind, apparently deriving their inflow from different sources. Cases of storm merger and splitting were observed. After 1830 MDT, one large cell at the southern end of the line began to dominate, moving up to 60° left of the mean wind. At this time, most of the other cells in the mesoscale complex dissipated. The large cell exhibited supercell characteristics and substantial modification of the environmental flow. After 2000 MDT, this cell moved northwestward out of South Park, while cold outflow air covered most of the Park.

This concludes the case study of July 19, 1977. This case is useful because it provides a detailed look at mesoscale convection within the surface and Doppler radar data networks, and because it provides an example of strong mesoscale forcing by the mountain-plains contrast. However, this case study is not pertinent to the general problems of west-to-east propagation and high plains mesoscale precipitation. In the next chapter, we will study August 4, 1977, the most ideal day in the SPACE 1977 data set for studying these processes.

4.0 4 AUG 1977 CASE STUDY - AN EASTWARD PROPAGATING MESOSCALE CONVECTIVE SYSTEM

The pattern of convective activity on August 4, 1977 contrasted sharply with that on July 19. On August 4, mountain thunderstorms which formed at about 1300 MDT propagated rapidly toward the east. A mesoscale squall line formed at the eastern edge of the mountains at about 1400 MDT. This tornado-producing storm then propagated south-eastward through the Palmer Lake Divide area, becoming progressively more intense as it gained access to larger amounts of low-level moisture. As the storm moved into western Kansas at about 2100 MDT, the area of intense convection and precipitation shifted northward into north-western Kansas, where about 50 mm of rain (∿15% of their mean for the entire summer) fell over an extensive area. The precipitation from this storm system fell on a time schedule roughly corresponding to the diurnal maximum of heavy precipitation presented in chapter 2 (Crow, 1969; Wallace, 1975).

August 4 was chosen as one of the "rapid scan" satellite days. High resolution satellite photos of the SPACE/HIPLEX study area were taken at intervals of either 3 minutes or 9 minutes during the period 1100 MDT - 1900 MDT. In addition to a complete set of SPACE/HIPLEX rawinsonde flights, supplementary 1200 MDT rawinsondes were taken at five NWS upper air stations (DEN, GJT, DDC, AMA, LBF). Two Bureau of Reclamation sponsored cloud physics aircraft (1MR and 1OUW) made cross-sectional flights from South Park to Goodland, Kansas and back during the time period 1310 - 1845 MDT (Danielson and Cotton, eds., 1977).

August 4 was also the first day on which substantial data are available from the CSU FPS-18 radar (CBS-4). CSU boundary layer profiler (BLP) data were taken starting at sunrise from two different locations - the base and a location 2.4 km west of the base, near the edge of the foothills of the Mosquito Range.

This day was chosen for intensive analysis because it provides a well-documented example of a significant mesoscale convective storm which appears to have had its origins in diurnal, terrain-induced dynamics and thermodynamics. The sequence of events from sunrise through to the next morning exhibits many of the diurnal characteristics reviewed in chapter 2.

4.1 4 August 1977 - Synoptic Situation

At 0600 MDT (1200 GMT) on August 4, winds at the 500 mb level were essentially zonal over most of the western U.S. (Fig. 41a). The band of stronger westerlies had receded northward, allowing light southwesterly winds, rotating around a weak subtropical high in New Mexico, to import moist Pacific air into the Rocky Mountain region. High dew points prevailed at 500 mb in Colorado as well as to the east and west. Wind speeds over Colorado were 12-15 m s^{-1}. At 700 mb (Fig. 41b), a mesoscale trough was present in western Kansas. Winds at Goodland, near the trough axis, were northerly, advecting cooler air from the northeast southward.

At the surface (Fig. 42), the 700 mb trough was reflected in an elongated low pressure center. At 850 mb, or about 500 m above ground level, a low level jet coincided with the location and orientation of

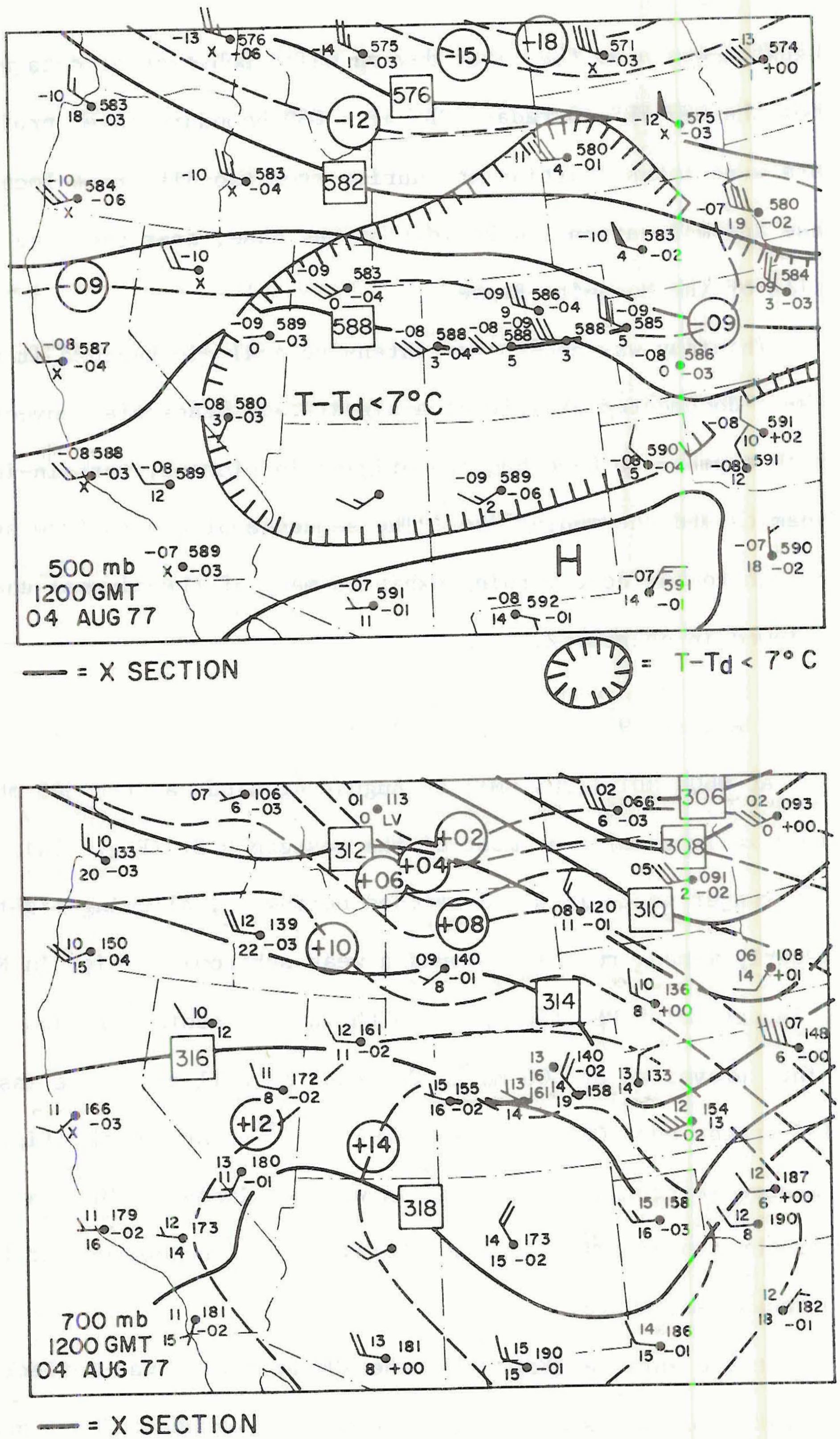


Figure 41. Upper air analyses as in Fig. 13, for a) 500 mb and b) 700 mb levels, 0600 MDT, 04 August, 1977.

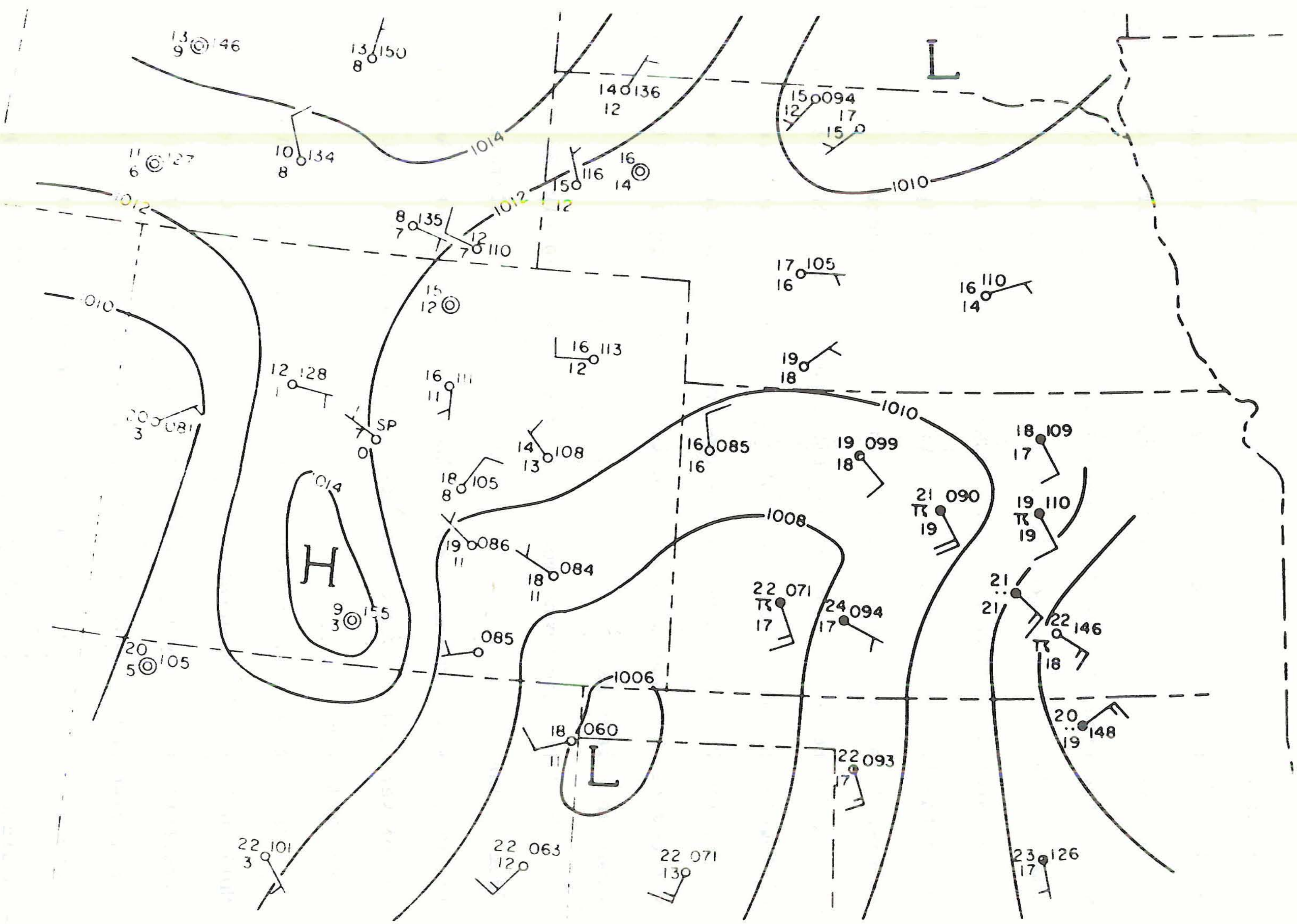


Figure 42. Extended area surface analysis, similar to Fig. 14, for 0600 MDT, 04 August 1977.

this low pressure center, with 850 mb winds of 21 m s^{-1} at Amarillo, TX (AMA) and 18 m s^{-1} at Dodge City, KS (DDC), both wind directions being about 210°. Surface winds within and east of this low were 5-10 m s^{-1} from the south or southeast, with high dew points (up to 23°C), overcast skies and precipitation. This precipitation was part of a large area of nocturnal precipitation visible on satellite IR images (Fig. 43). Strikingly, this thunderstorm region was centered on the area which has a climatological nocturnal precipitation maximum, while the low-level jet appears also in its climatologically most favored location (Bonner, 1968). The relative orientation of the jet to the region of convective storms seems compatible with the concept of low-level convergence ahead of the jet presented by Pitchford and London (1962). Northwest of the low pressure area, eastern Colorado was covered by somewhat cooler, drier air, with light north to west winds and clear skies.

The large nocturnal mesoscale system shown in Fig. 43 had developed from a line of cells which had formed over eastern Colorado and Wyoming the previous afternoon (3 Aug). In South Park, however, August 3 was a day of very little convective activity because of the lack of boundary layer moisture.

An east-west cross section of soundings taken at 1200 GMT (0600 MDT) on August 4 is shown in Figure 44. The potential temperature structure was fairly flat with the Limon sounding slightly warmer in the lowest layer, similar to the thermal pattern on July 19, but less pronounced. Low-level moisture had a strong east-west gradient, with Goodland having about 8.8 gm kg^{-1} average in the lowest 100 mb (about

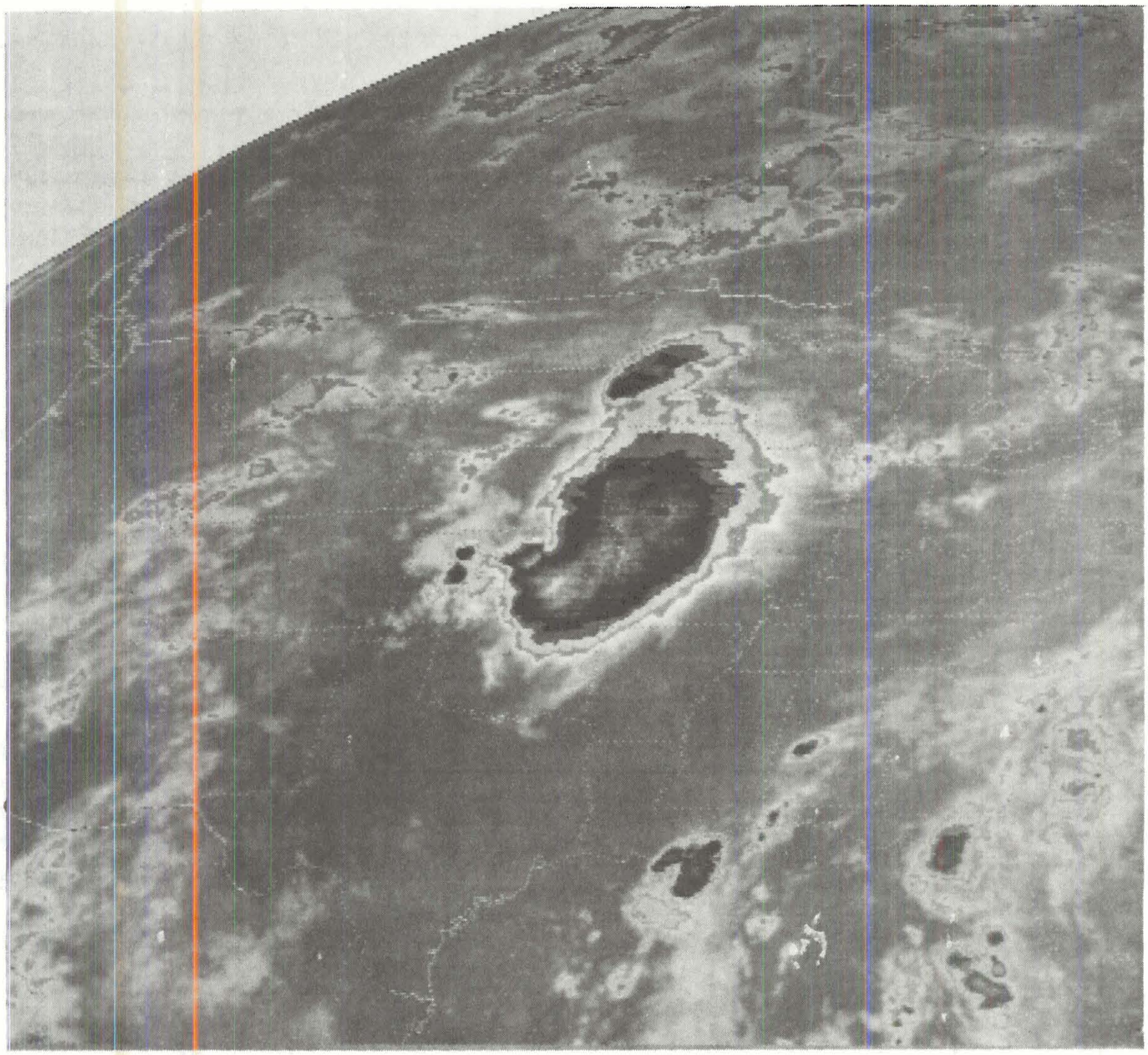


Figure 43. Satellite infrared (IR) image of western U.S., similar to Fig. 15, for 0400 MDT, 04 August 1977. The huge mesoscale convective storm in the central plains is descended from storm systems which formed in eastern Colorado the previous day, (03 August 1977).

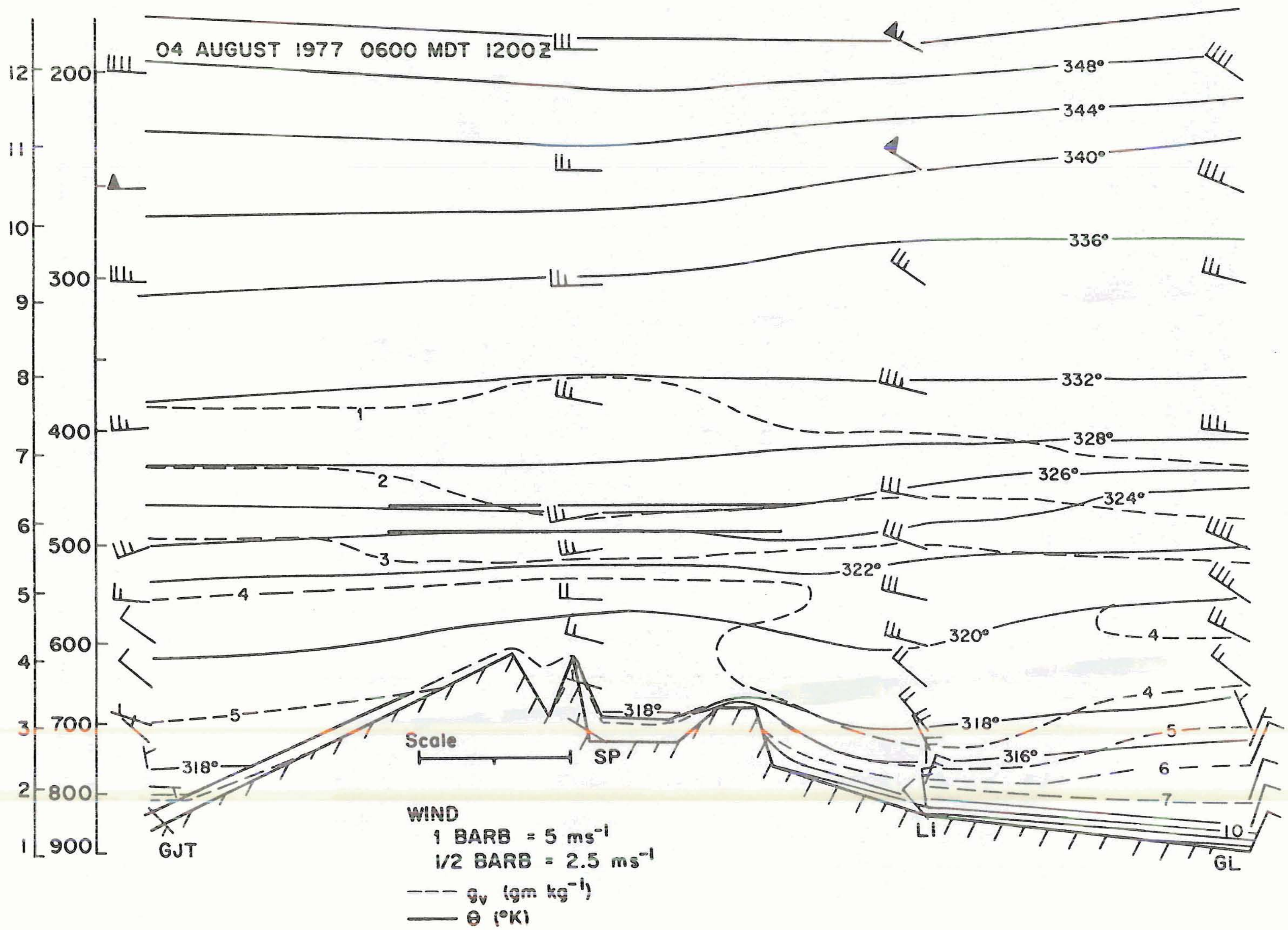


Figure 44. East-west cross-section, as in Fig. 21, for 0600 MDT, 04 August 1977.

1.2 km), Limon with 6.8 gm kg^{-1} and South Park with 4.8 gm kg^{-1}. All stations had about 3 gm kg^{-1} at 500 mb, indicating that little large-scale subsidence was present. A stable region at about 500 mb seemed to be strongest over South Park, perhaps indicating mesoscale subsidence due to nocturnal drainage winds from the mountains. Thus, the bold lines representing the boundaries of this elevated stable layer in Fig. 44 extend roughly over the region of high terrain in central Colorado.

Winds were generally westerly aloft, 12-25 m s^{-1}. Winds below 660 mb were northerly at Limon and Goodland, indicating cool advection which would tend to increase thermal stability of the atmosphere. However, this cool northerly air was not significantly drier than the air it replaced, since the Great Plains were covered with subtropical moisture all the way into Canada at this time of year. The winds at South Park had almost no directional shear, indicating little or no thermal advection at any level.

4.2 4 August 1977 - Evolution of the Planetary Boundary Layer

In the previous section, the initial vertical and horizontal structure of the atmosphere on a scale larger than South Park just before sunrise (0600 MDT) on August 4 was depicted. In this section, surface data (PAM), rawinsondes, and tether balloons are used to describe the finer scale structure of the atmosphere over South Park and the modifications to this structure which resulted from solar heating of the surface. The progressive deepening of the boundary layer which, along with various terrain effects, induced the first cumulus clouds to form at approximately 1000 MDT over the Mosquito Range, and which also produced an environment favorable for deeper precipitating cumulus convection at about 1200 MDT is shown.

At 0600 MDT, the South Park sounding (Fig. 45) had a very thin, sharp surface radiation inversion. Above the inversion, an essentially neutral layer extended to 630 mb, or about 2.3 km above the surface. Westerly winds increased by 7-10 m s^{-1} within this layer, with very little directional shear. Above 630 mb, the middle troposphere was stratified into several thin mixed layers, separated by stable layers. The strongest stable layer was at about 480 mb, near the average upper inversion level observed by Huggins (1974). This stable layer was postulated to be a consequence of general subsidence over the mountains due to downslope winds, as described in the previous section. The average mixing ratio in the lowest 100 mb was 4.8 gm kg^{-1}. The level on this sounding at which this amount of moisture would reach saturation is the mixed condensation level, or MCL, which is an estimate of the subsequent convective cloud base. A cloud with its base at the MCL of 520 mb would be capped by the inversion at 480 mb. If this inversion were eliminated, the cloud parcel could then rise to at least 310 mb (9 km MSL) before losing buoyancy. Above this level, a strongly stable lapse rate was present up to the tropopause.

Surface winds, θ, and q_v for this time (Fig. 46a) show that very light winds were prevalent within the Park, basically flowing downhill below the nocturnal inversion. Most wind directions were toward the regions of lower potential temperature in low-lying valleys in the center of South Park. Water vapor mixing ratios were almost uniform throughout South Park, averaging about 5.5 gm kg^{-1}. After sunrise, at 0700 MDT (Fig. 46b), all the stations began to heat up, with wind

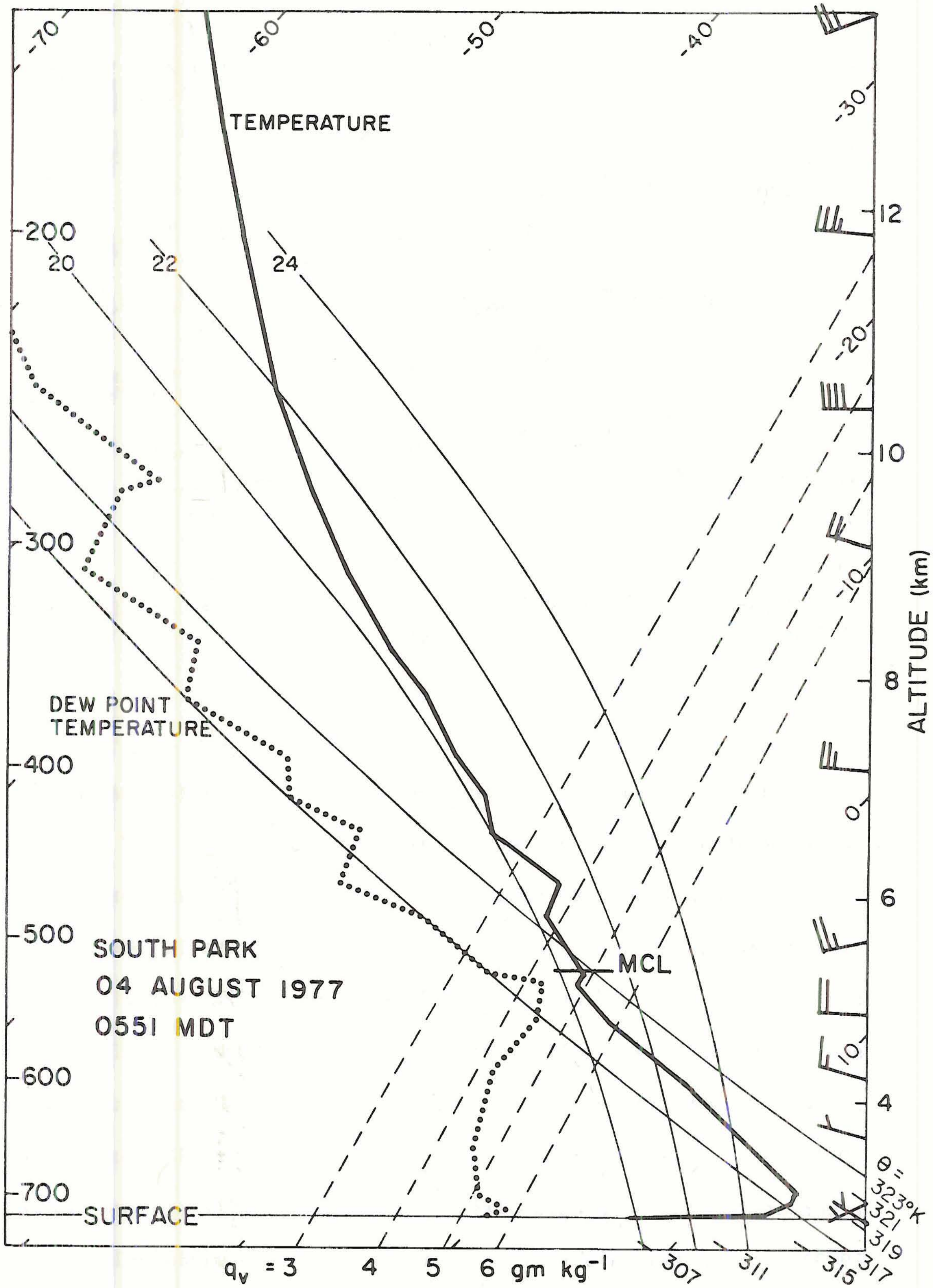
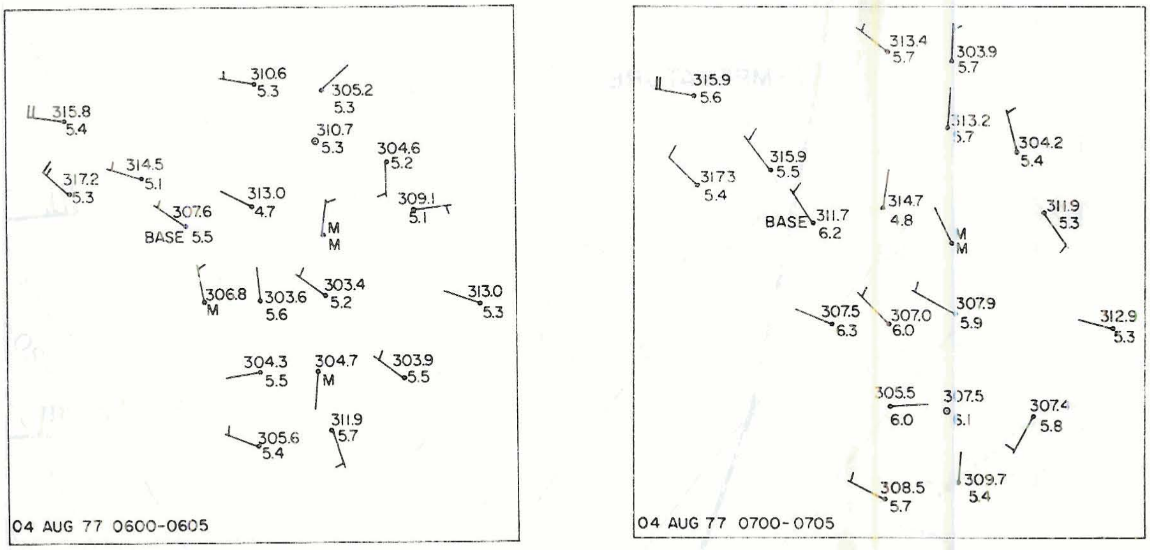


Figure 45. South Park sounding of 0551 MDT, 04 August 1977, plotted on skew-T log-P diagram.



a) b)

Figure 46. PAM surface data from South Park, as in Fig. 18, for a) 0600 MDT and b) 0700 MDT, 04 August 1977.

directions still basically downslope. Mixing ratios had begun to increase at a majority of the stations.

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 ("Site Number 2"). A similar system set up at the base itself failed to operate on August 4. The working BLP 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 published (Banta and Cotton, 1979). These indicate that the morning downslope winds below the radiation inversion switched to upslope 1-2 hours after sunrise. Upslope winds formed in a thin convective boundary layer which was

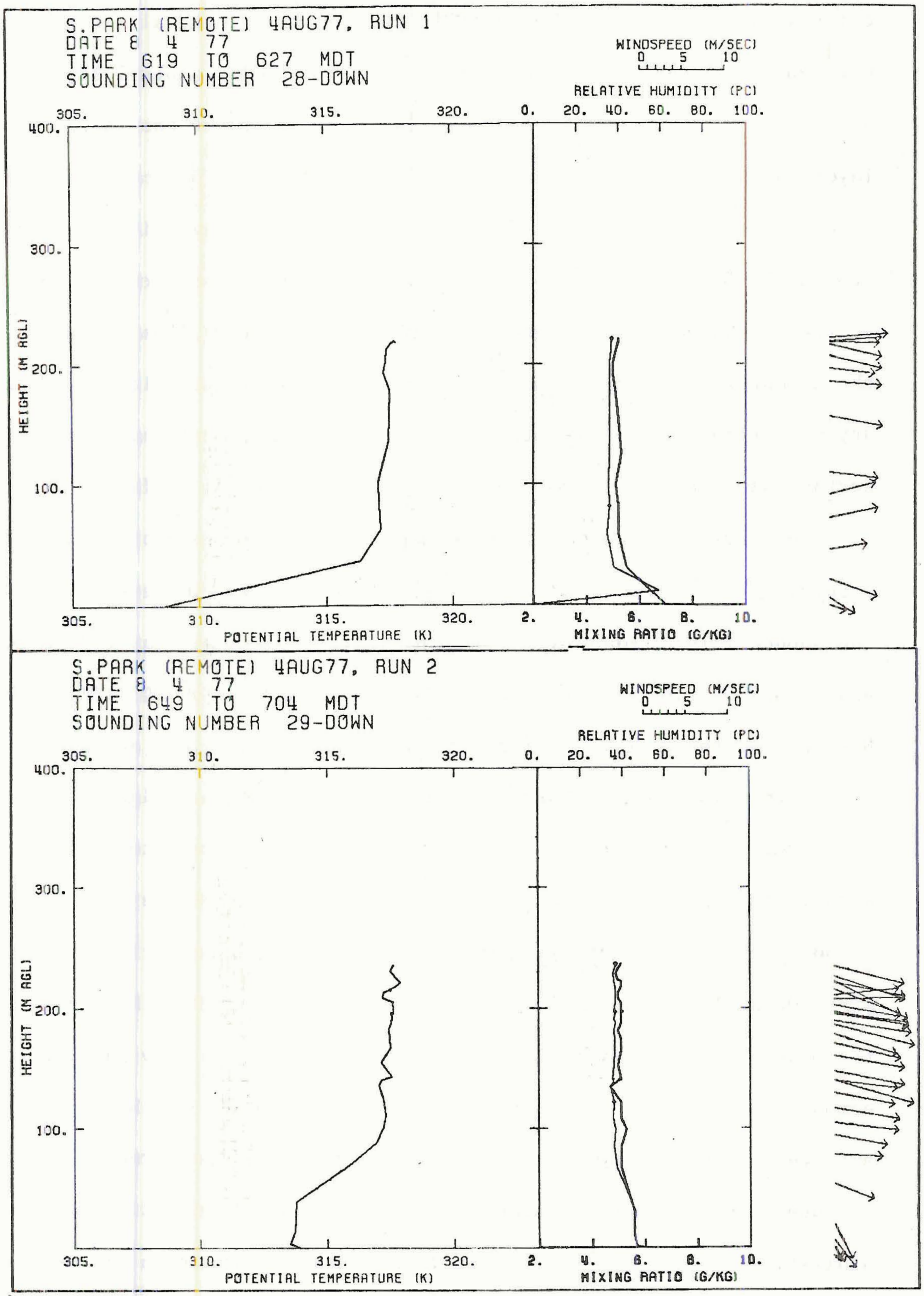


Figure 47. Boundary Layer Profiler (BLP) tethered balloon soundings. Potential temperature, water vapor mixing ratio, and winds plotted against height in meters AGL. Soundings begun at a) 0619 MDT, and b) 0649 MDT, 04 August 1977, both at Site #2.

potentially cooler than the neutral layer above. Vertical mixing between the convective boundary layer and the deeper neutral layer aloft did not occur until the potential temperature of the boundary layer had increased by diabatic heating to match the potential temperature of the neutral layer. On the dry suppressed convective cloud 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 a rapid decrease in surface moisture.

On August 4, however, a somewhat different sequence of events occurred. The soundings from Site #2 (Fig. 47) show the evolution of the boundary layer just after sunrise. A neutral mixed layer 40 m deep had formed within the nocturnal inversion by about 0700 MDT (Fig. 47b). Notice that the potential temperature at about 50 m, just above the top of this layer, <u>decreased</u> by several degrees between Figs. 47a and 47b after sunrise. This was due to entrainment of the potentially-warmer air at this level downward into the cooler mixed layer. Winds on both of these soundings were basically downslope westerlies up to over 200 m, the maximum sounding altitude. By about 0730 MDT (Fig. 48a), the mixed layer was about 100 m deep at Site #2, with very light winds compared to the continued strong westerlies above 100 m. Winds at the surface had swung around almost to an easterly upslope direction. The θ lapse rate was somewhat stable near the surface, indicating the possibility of cool advection by the upslope winds nearest to the surface.

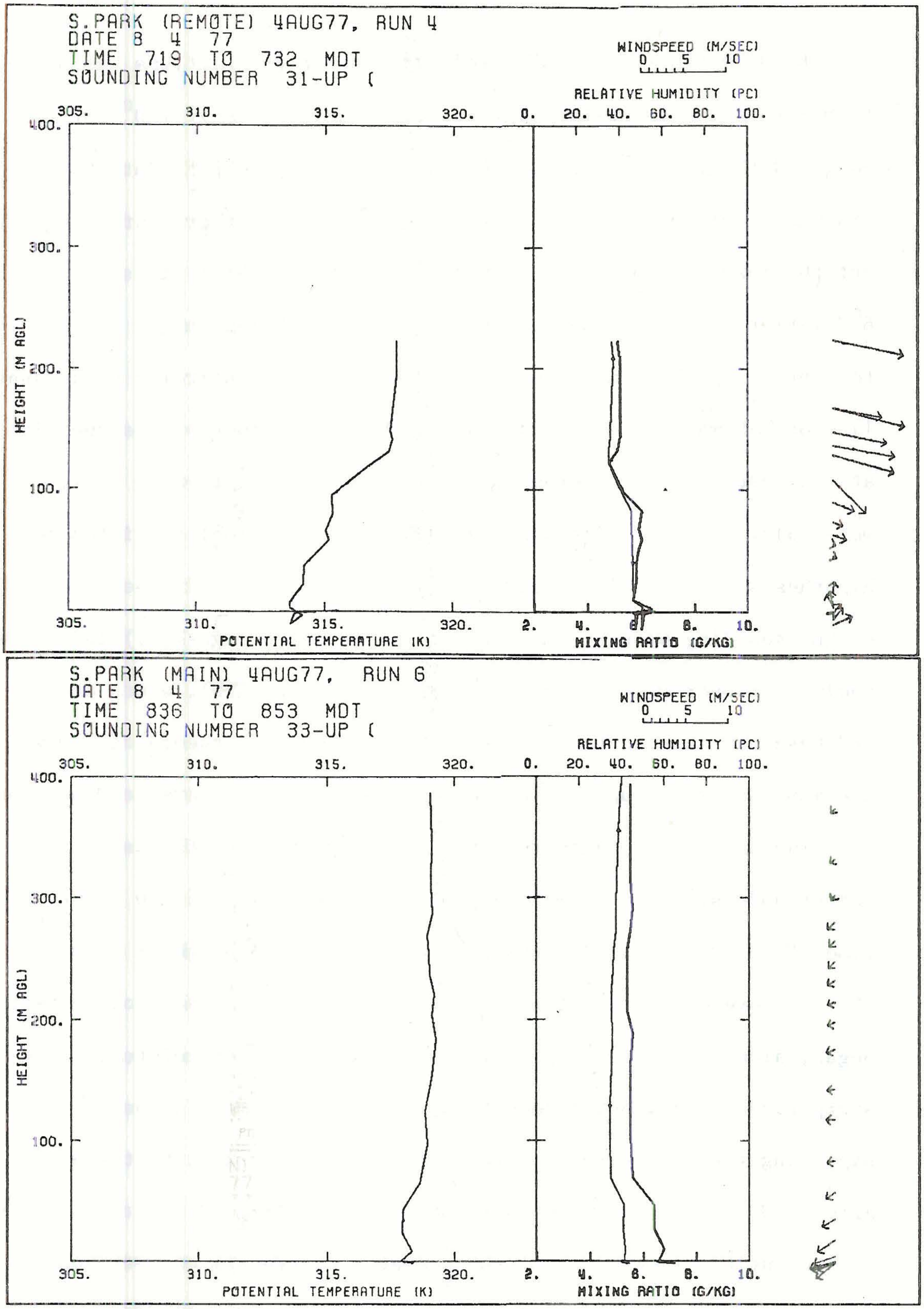


Figure 48. Same as Fig. 47, for a) 0720 MDT, Site #2, and b) 0836 MDT, Site #1 (CSU base site).

By 0800 MDT (Fig. 49a), winds at several PAM stations had begun to shift toward an upslope direction, which is roughly 150° for the CSU base and the valley locations to the southeast. BLP flights at the CSU base location show very light winds with a northerly drift throughout the lowest 300 m of the atmosphere. The CSU base was still up to $6^{\circ}K$ warmer in θ than the low-lying valleys. Mixing ratios had increased to over 6.5 gm kg^{-1} at some valley PAM stations (encircled by a dashed line on PAM maps, Figs. 49 and 51). Thus, the onset of upslope winds at the base should have resulted in low-level advection of cool, moist air. A BLP flight begun at 0836 MDT (Fig. 48b) confirmed this hypothesis. Winds with a stronger upslope component in the lowest 50 m of the sounding brought increased moisture (to 6.5 gm kg^{-1}) and somewhat cooler air over the CSU base. By 0900 MDT (Fig. 49b), winds at the CSU base had shifted to the upslope direction with speeds of 5 m s^{-1}. The base was still up to $4^{\circ}K$ warmer in θ than the downvalley locations.

The pattern of boundary layer evolution at the CSU base can be better understood by examining a plot of surface θ and dew point vs. time (Fig. 50). After sunrise, θ rose rapidly until about 0820 MDT, when it leveled off at about $\theta = 317.5^{\circ}K$. At this time, cool advection began, along with very rapid fluctuations in surface moisture. The sharp rises in dew point seem to correlate with small drops in θ, signaling the arrival of a parcel of cool, moist river bottom air. After 0900 MDT, θ began to increase again, but it did not reach $321^{\circ}K$, the potential temperature of the elevated neutral layer over South Park on August 4 (as determined from rawinsondes) until after 1100 MDT.

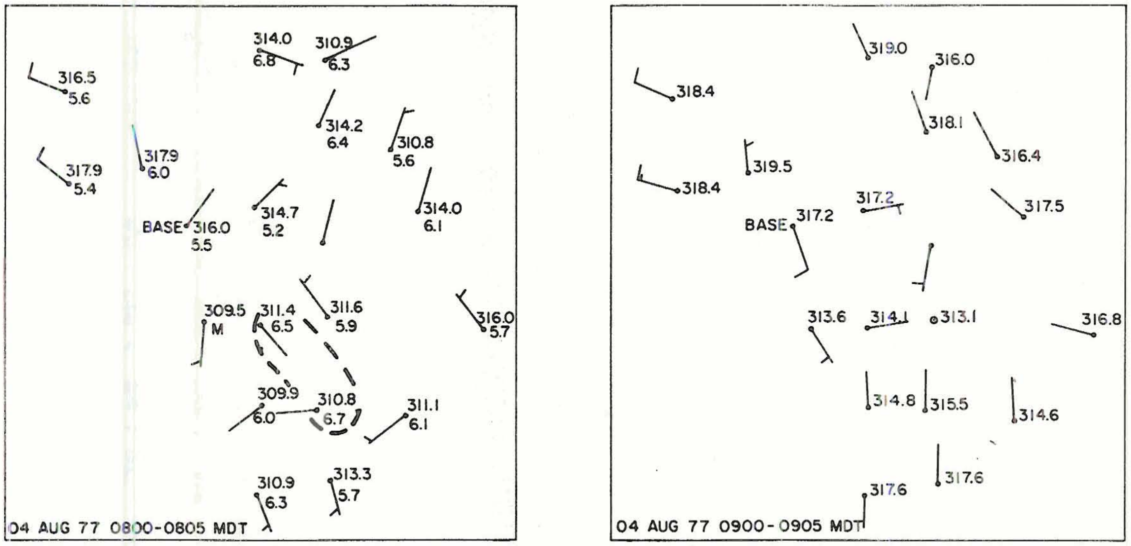


Figure 49. Same as Fig. 46, for a) 0800 MDT, and b) 0900 MDT, 04 August 1977 (water vapor mixing ratio data missing for 0900 MDT). Dashed line encloses region with mixing ratio >6.5 gm kg^{-1}.

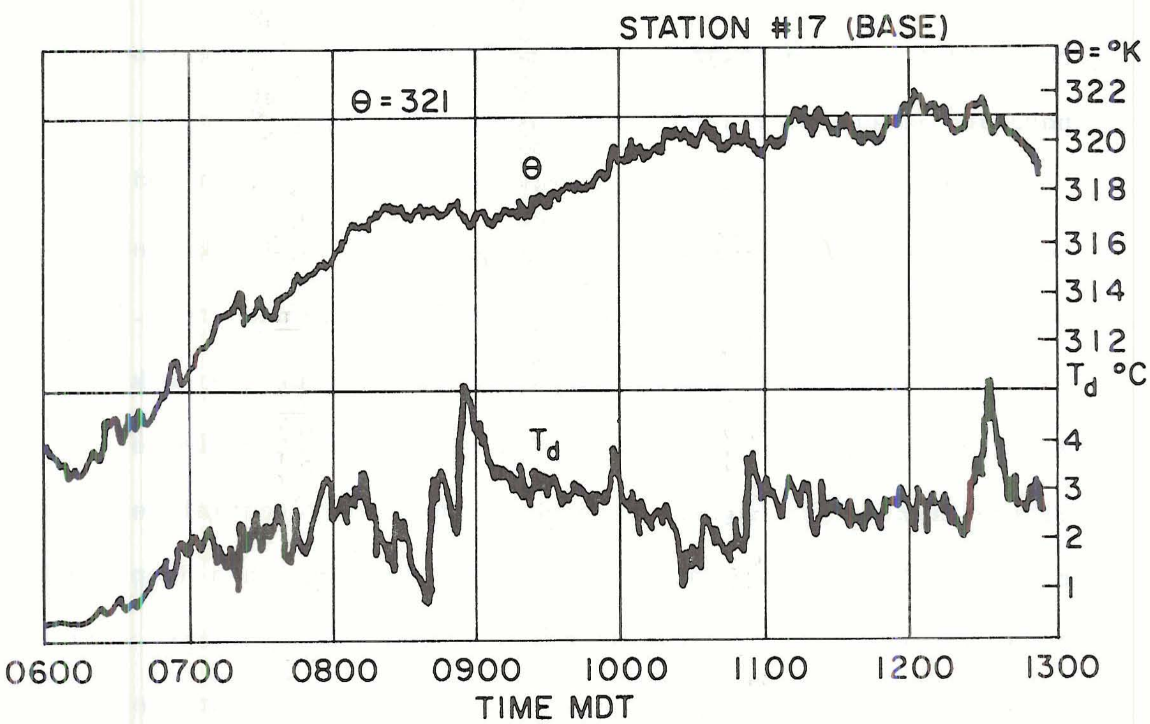
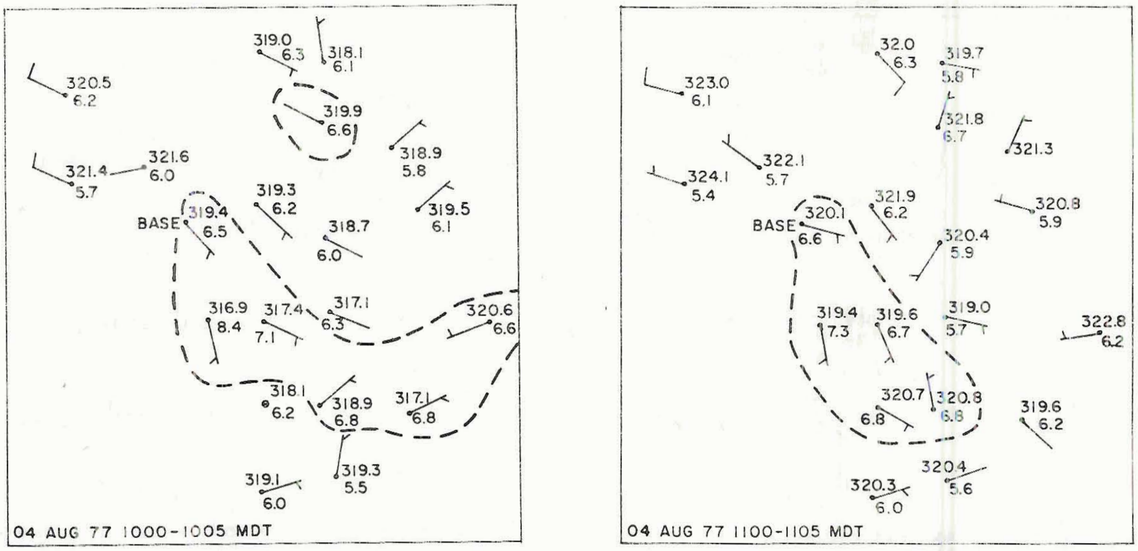


Figure 50. Plot of potential temperature and dew-point vs. time, at the CSU base, 0600-1300 MDT, 04 August 1977.



a) b)

Figure 51. Same as Fig. 46, for a) 1000 MDT, and b) 1100 MDT, 04 August 1977.

Thus, growth of a deep, well-mixed PBL, in which surface parcels could rise to saturation by buoyant forces, did not occur over the base and lower-lying areas until after 1100 MDT.

A pattern of light but coherent valley winds prevailed in central South Park at 1000 MDT (Fig. 51a). The gradient of θ between the CSU base and the coldest valley location had been reduced to 2.5^{o}K. A large number of stations had mixing ratios of over 6.5 gm kg^{-1}. The location of these stations coincided well with the valley of the South Platte River. The higher western stations had potential temperatures of up to 321.6^{o}K, indicating that convection through a deep boundary layer was possible at those locations. In fact, the first small cumulus clouds were observed over the Mosquito Range at about 1000 MDT. Data suggesting the origin of these cumulus clouds will be examined in a subsequent paragraph.

The effect of cool upslope advection on the South Park environment, as well as possible effects of early cumulus convection, are revealed in the 1030 MDT rawinsonde (Fig. 52). A nearly-neutral layer extended up to 580 mb, or 1.6 km AGL. Winds in this layer were very light, switching from easterly at the surface to westerly at 580 mb. Potential temperature increased from 320^{o}K near the surface, to 321^{o}K at 580 mb, while the moisture mixing ratio decreased from 6.3 gm kg^{-1} to 5.2 gm kg^{-1}. These vertical gradients in momentum, moisture and potential temperature can be partially attributed to low-level upslope winds.

Above 580 mb, the 1030 MDT rawinsonde has a layer of relatively moist, conditionally unstable air extending up to 430 mb. This is the layer in which the first cumulus clouds formed. Westerly winds increased by about 10 m s^{-1} within this layer. The potential temperature inversion at 480 mb which had been present at 0600 MDT (Fig. 45) was almost entirely eliminated. A low-level parcel with a mixing ratio of 6 gm kg^{-1}, if lifted on this sounding, would reach saturation at about 540 mb, and could then rise to a potential cloud top of 270 mb (10 km AGL) before losing buoyancy.

The onset of rapid PBL growth as indicated by surface potential temperature, had occurred or was imminent over most of South Park by 1100 MDT (Fig. 51b). Less than 1^{o}K θ difference remained between the CSU base and the valley stations. Thus, with a smaller θ gradient, the cool advection due to upslope winds should have decreased, allowing growth of a deeper neutral PBL. A BLP sounding taken at this time (Fig. 53) shows a well-mixed PBL to at least 350 m, with θ = 320°K and q_v > 6 gm kg^{-1} in upslope winds. A thin (20m) superadiabatic surface layer can also be seen.

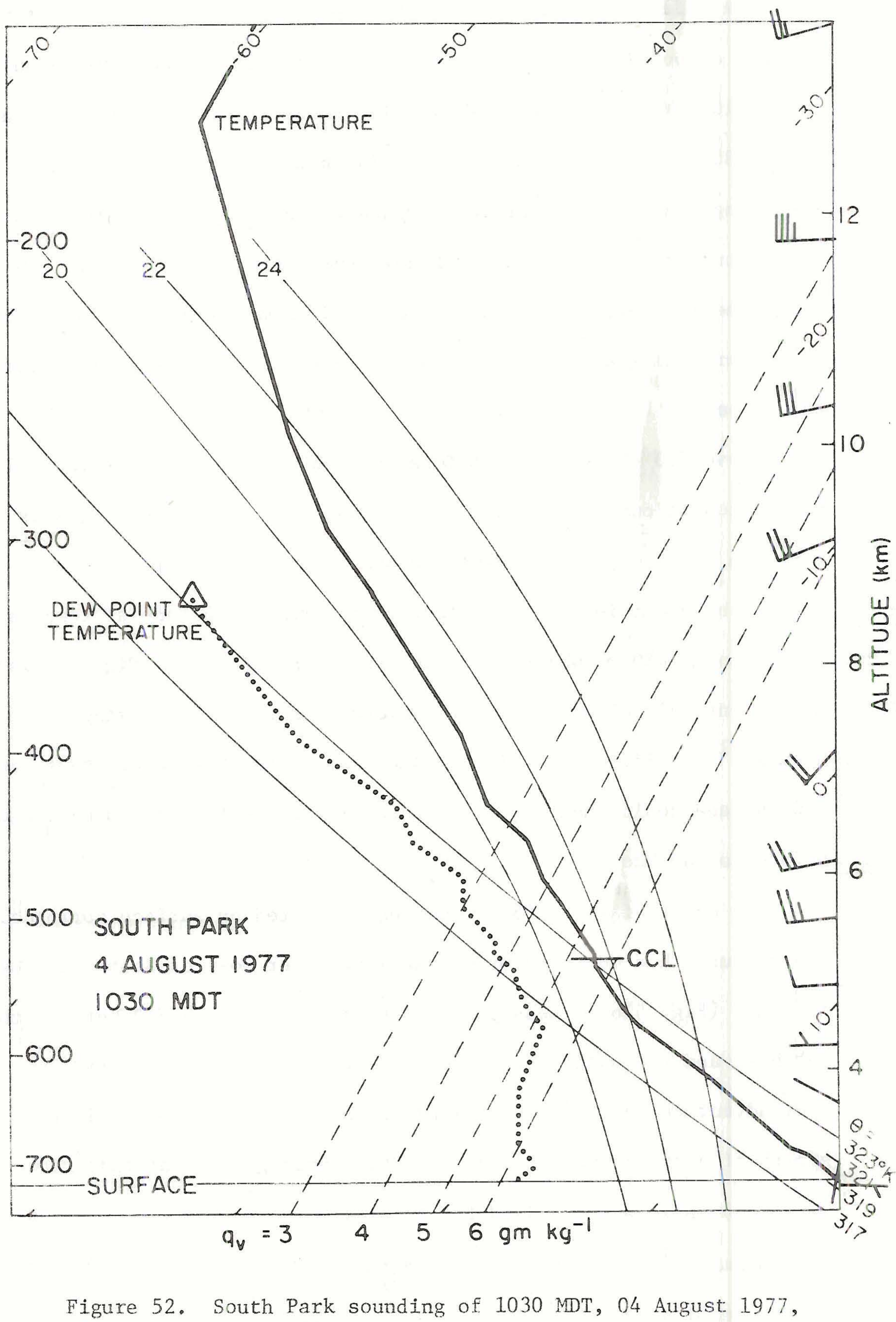
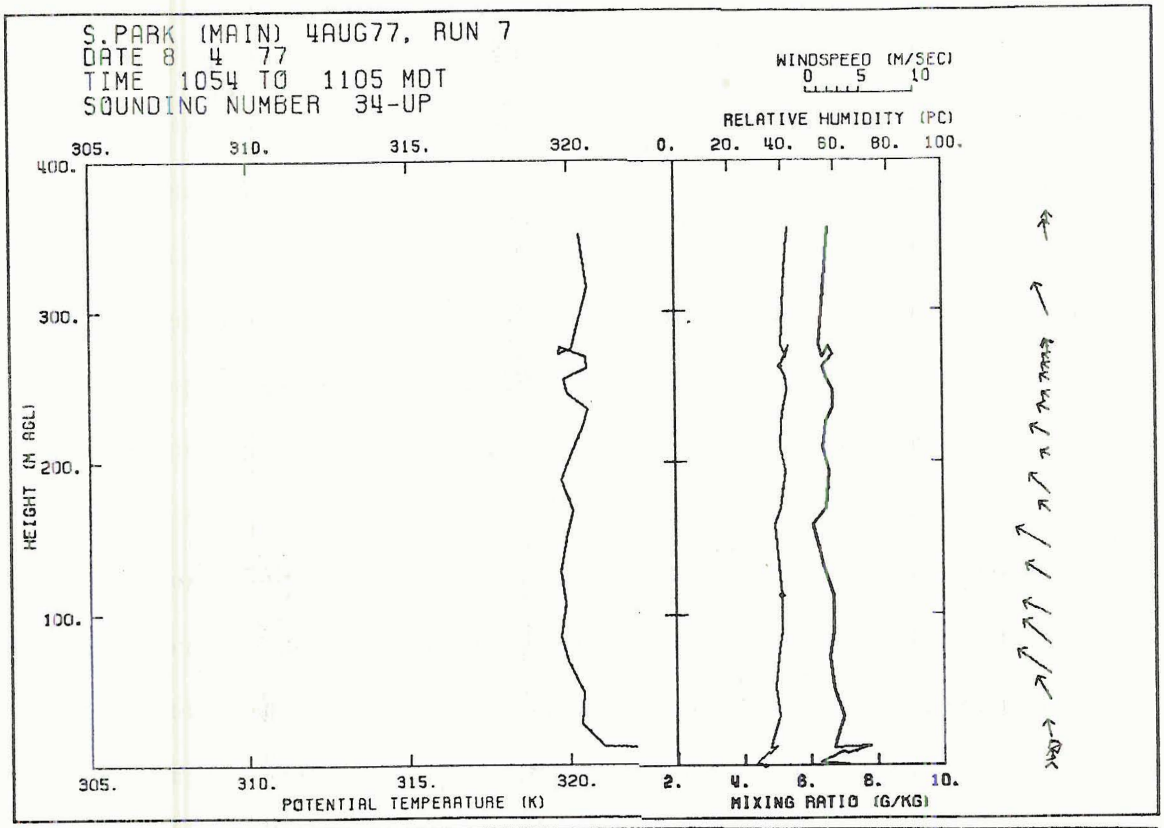


Figure 52. South Park sounding of 1030 MDT, 04 August 1977, plotted on skew-T log-P diagram.



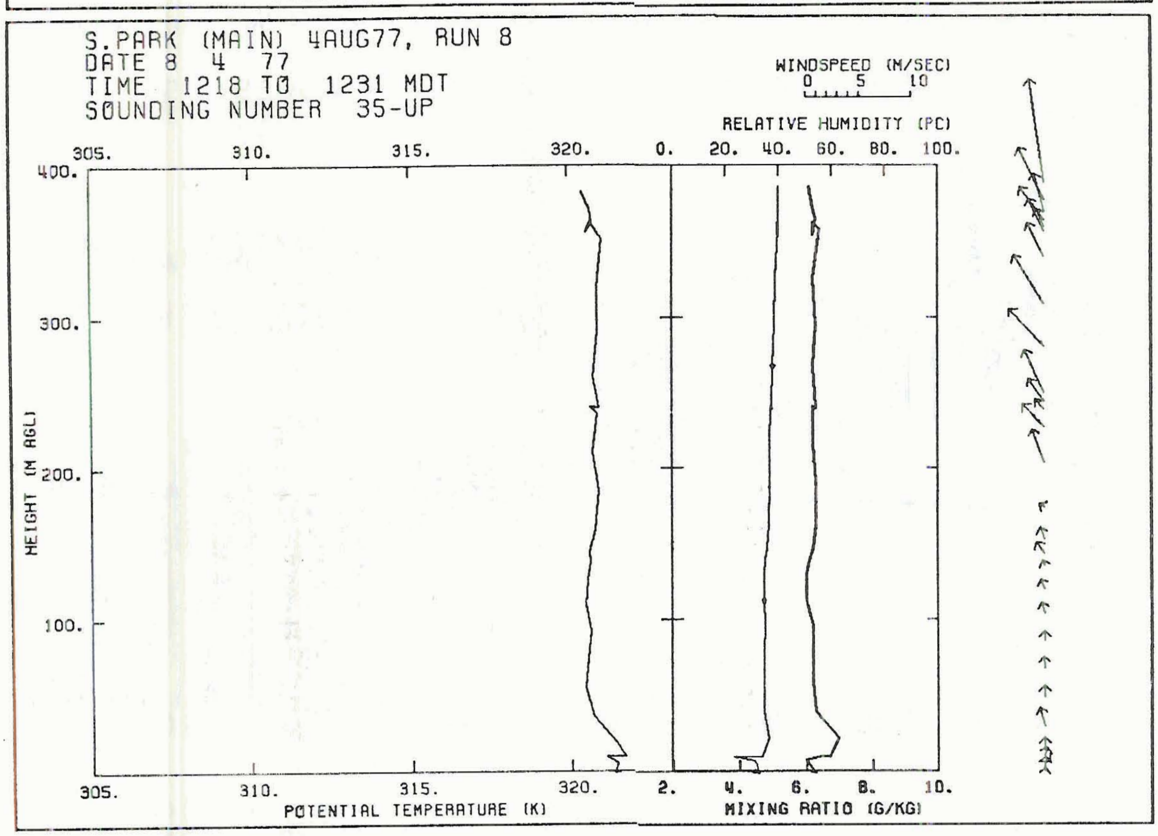


Figure 53. Same as Fig. 47, for a) 1054 MDT, and b) 1218 MDT, taken at Site #1 (CSU base).

The initial stability and valley wind effects which prevailed over lower areas of South Park in the morning 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 ridges of the Mosquito Range (at 1100 MDT, Fig. 51b) during the same time period, indicating that deeper PBL growth had already occurred. The time evolution of the convection in this deeper PBL is revealed in Fig. 54, a time plot of θ, dew point, and wind velocity at station 6, which was located on Horseshoe Peak at an elevation of over 4.2 km MSL (615 mb). Shortly after 0900 MDT, θ trended sharply upward, while the wind speed fell off sharply. Just before 1000 MDT, another sharp rise to θ = 323°K was accompanied by a drop in wind speed. Moisture remained relatively constant at 5.5 gm kg^{-1}. The 1030 MDT South Park rawinsonde

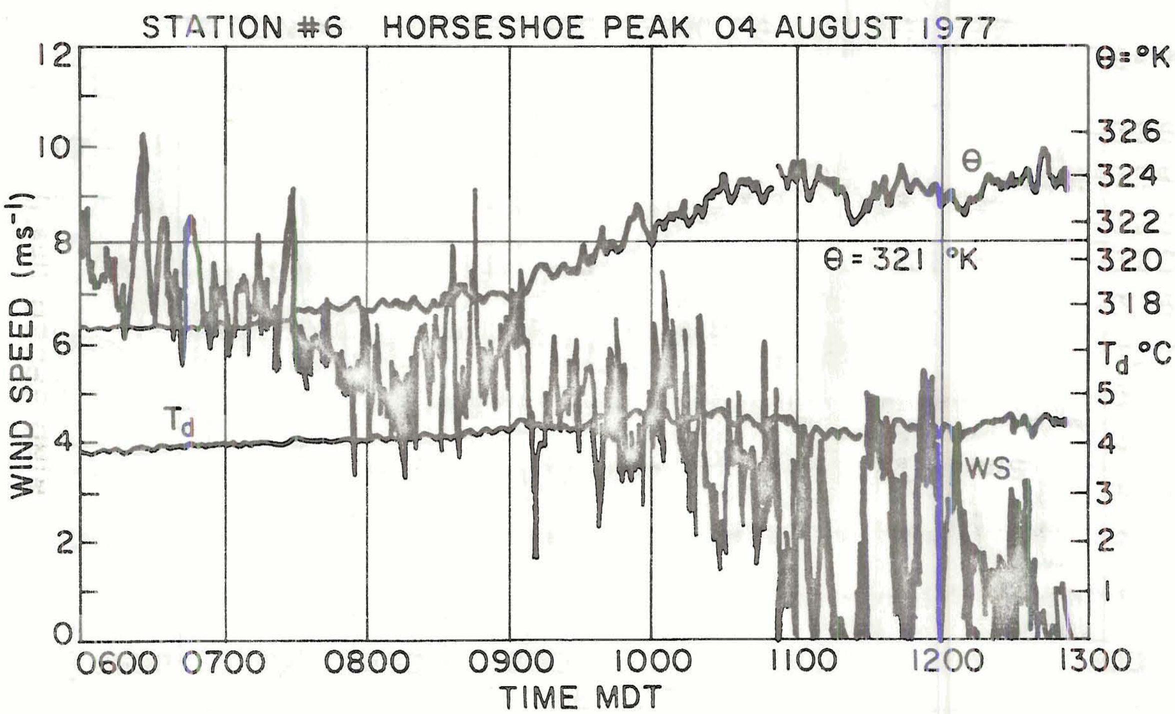


Figure 54. Temperature, dew-point, and wind speed plotted vs. time, at PAM station #6 (Horseshoe Peak), for 0600-1300 MDT, 04 August 1977.

(Fig. 52) shows that a parcel with $\theta = 323^{o}K$, $q_v = 5.5$ gm kg^{-1} might barely reach saturation and form a cloud with its base at 530 mb. It is hypothesized that the excursion in surface θ to $323^{o}K$ at Horseshoe Peak, with a corresponding marked decrease in wind speed, represents the formation of a large bubble of air which was heated to $2^{o}C$ temperature excess by insolation on the mountain peaks and slopes. The sudden decrease in θ at 1000 MDT, with a sudden rise in wind speed, may represent the entrainment of cooler free-environmental air (at $\theta = 321^{o}K$) moving in from the west in the wake of the rising bubble. After 1000 MDT, Horseshoe Mountain became an almost continuous source of cloud bubbles.

Favorable conditions for cumulus cloud formation over the Park did not occur until after 1200 MDT, when a potential temperature of $321^{o}K$ was present at most of the surface stations in South Park. A BLP sounding taken from the CSU base at about 1220 MDT, the time of the first radar echoes in South Park, is shown in Fig. 53b. A potential temperature of at least $320.5^{o}K$ with almost no vertical lapse is indicated, with mixing ratios of over 6 gm kg^{-1} in southeasterly upslope winds.

To summarize the boundary layer evolution leading up to deep cumulus convection, nocturnal drainage winds served to move cool, stable air to the low, flat areas of the Park, while inhibiting the growth of a deep surface radiation inversion on the steeper mountain slopes. 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 over the entire Park after 1200 MDT.

Observed slope 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 sunrise 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. The observed increases in surface moisture at many surface stations were thus due to low-level and surface moisture initially within South Park. After sunrise, evaporation and transpiration may have increased, especially in moist, low-lying river bottoms. Since surface meteorological stations are usually located on local hilltops, advection of low-level moisture over very short distances could also have contributed to enhanced mixing ratios.

The case of July 19 and several other cases (some reported in Danielson and Cotton, ed., 1977) indicate that larger scale advection from the Plains eastward into South Park due to slope winds is most likely to occur in the late afternoon, in response to the generation of a Rocky Mountain thermal low pressure center by high-level topographic heating. Thus, advection of strong Gulf moisture into South Park is more likely to occur on the day before the thunderstorms which feed off this moisture occur. In the Front Range "hot spots", however, the advection of Plains moisture can occur on the same morning it is used.

4.3 4 August 1977 - Large-Mesoscale Cloud Environment

In the previous section, it was shown how the evolution of the planetary boundary layer over South Park on August 4 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 two hours. In this section, a similar phenomenon which occurred over a much larger area on a time scale of 6-12 hours is examined. Deep thunderstorms occurred over the moutainous areas of Colorado before 1300 MDT, while all cumulus convection was inhibited in the plains of eastern Colorado for several more hours.

In Figs. 55 through 57, rawinsondes, radars, surface weather stations and instrumented aircraft are used to depict the atmosphere over the region from the central Rockies east to Goodland, Kansas at 1200 - 1300 MDT, just as deep cumulonimbus convection was first forming over the mountains. The 1301 MDT South Park sounding (Fig. 55) shows the influence of this deep 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 50 mb (0.6 km AGL). Above this, the well-mixed neutral layer extended to 580 mb (1.7 km AGL), with light winds veering from 170° to 260°. The layer extending from 580 mb to 511 mb can be characterized as a layer of penetrative convection, which entrained mid-tropospheric air into the planetary boundary layer. This layer exhibited a very slight lapse rate of θ, decreasing moisture, and a 5 m s^{-1} increase in westerly

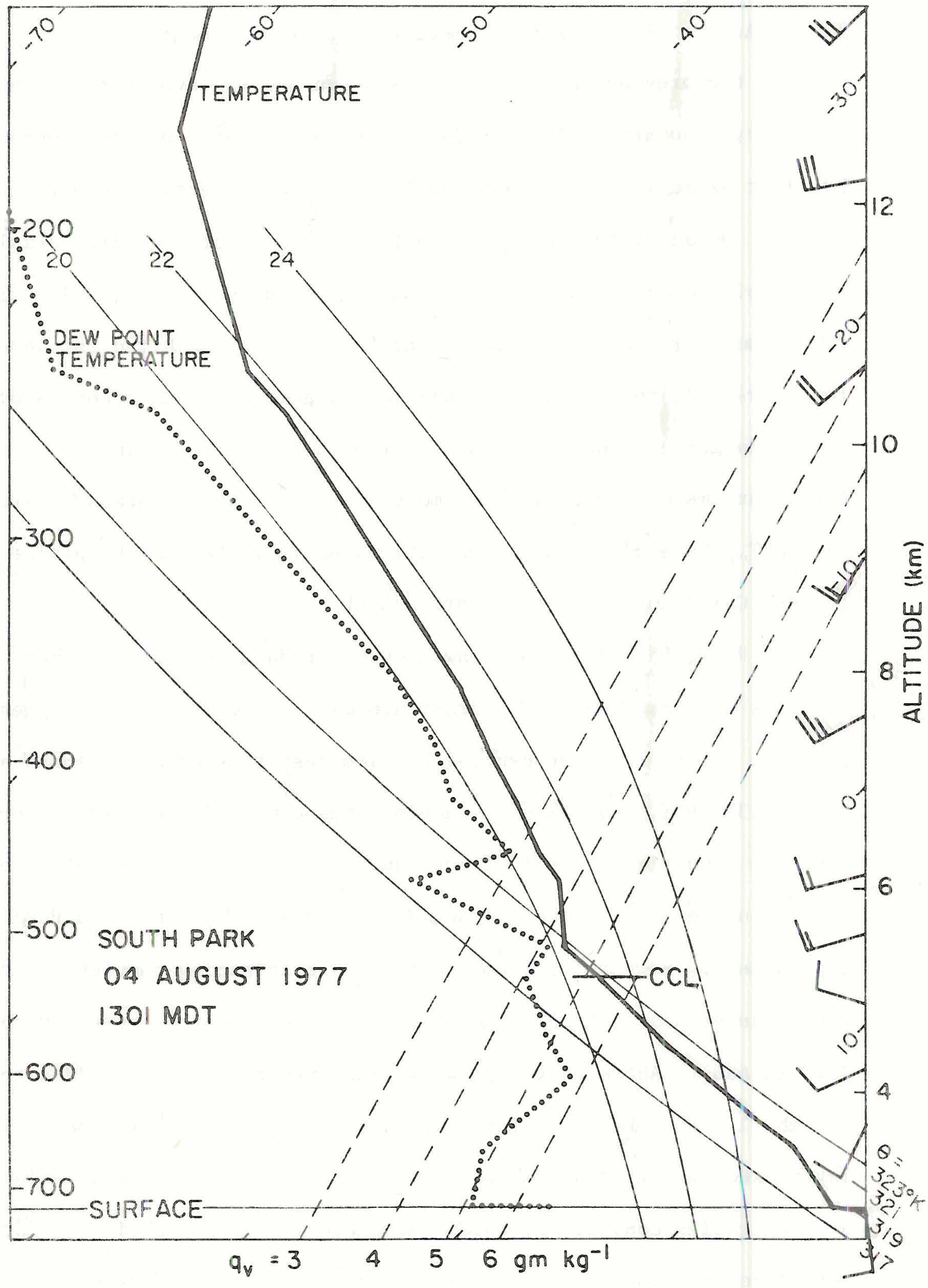


Figure 55. South Park sounding of 1301 MDT, 04 August 1977, plotted on skew-T log-P diagram. Cloud Condensation Level (CCL) marked.

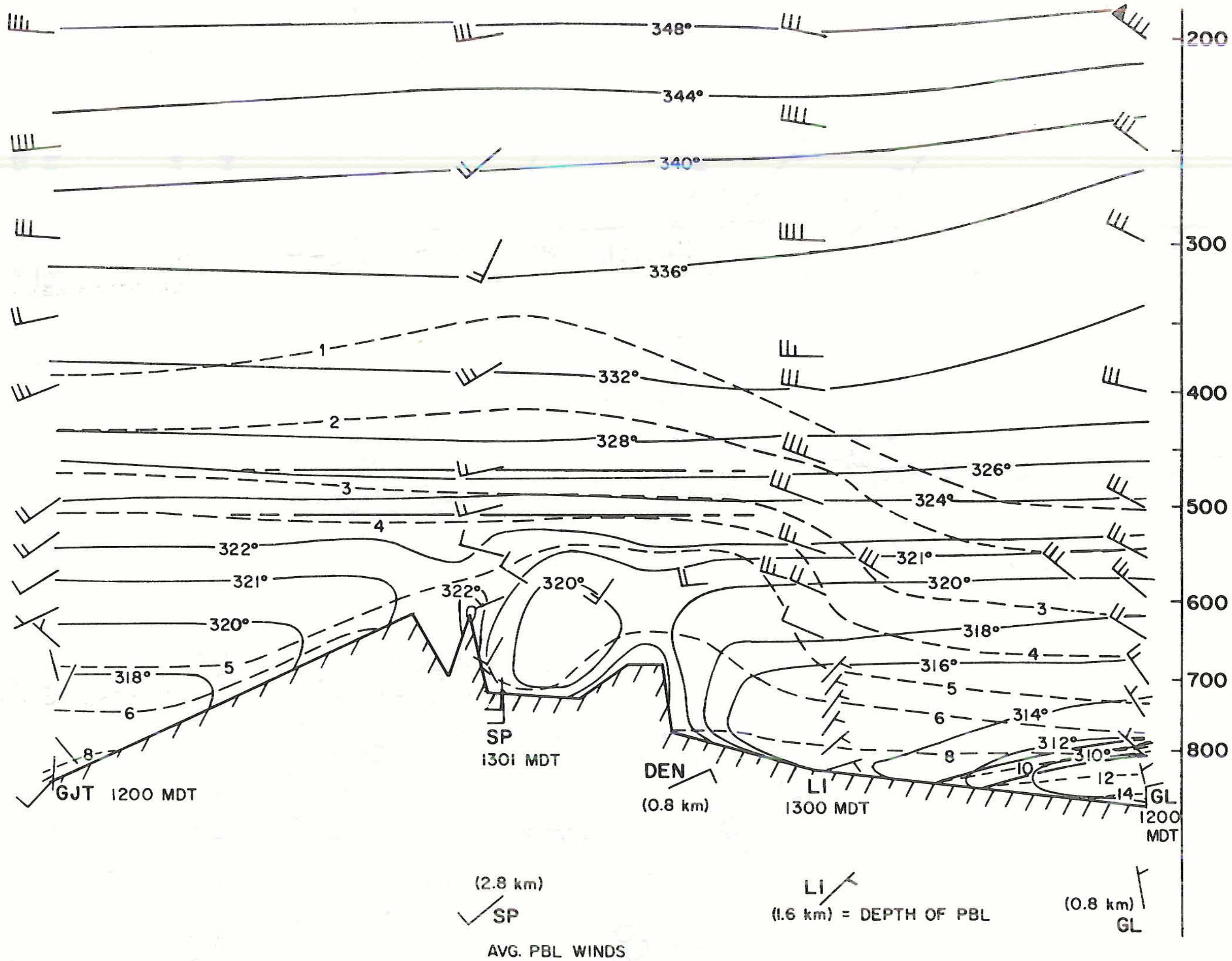


Figure 56. East-west cross-section, as in Fig. 17, for 1200-1300 MDT, 04 August 1977. Average winds in the PBL, along with PBL depth, are plotted for 4 stations (SP, LI, GL, and Denver) in the lower margin. Data from a west-to-east aircraft flight are included in analysis.

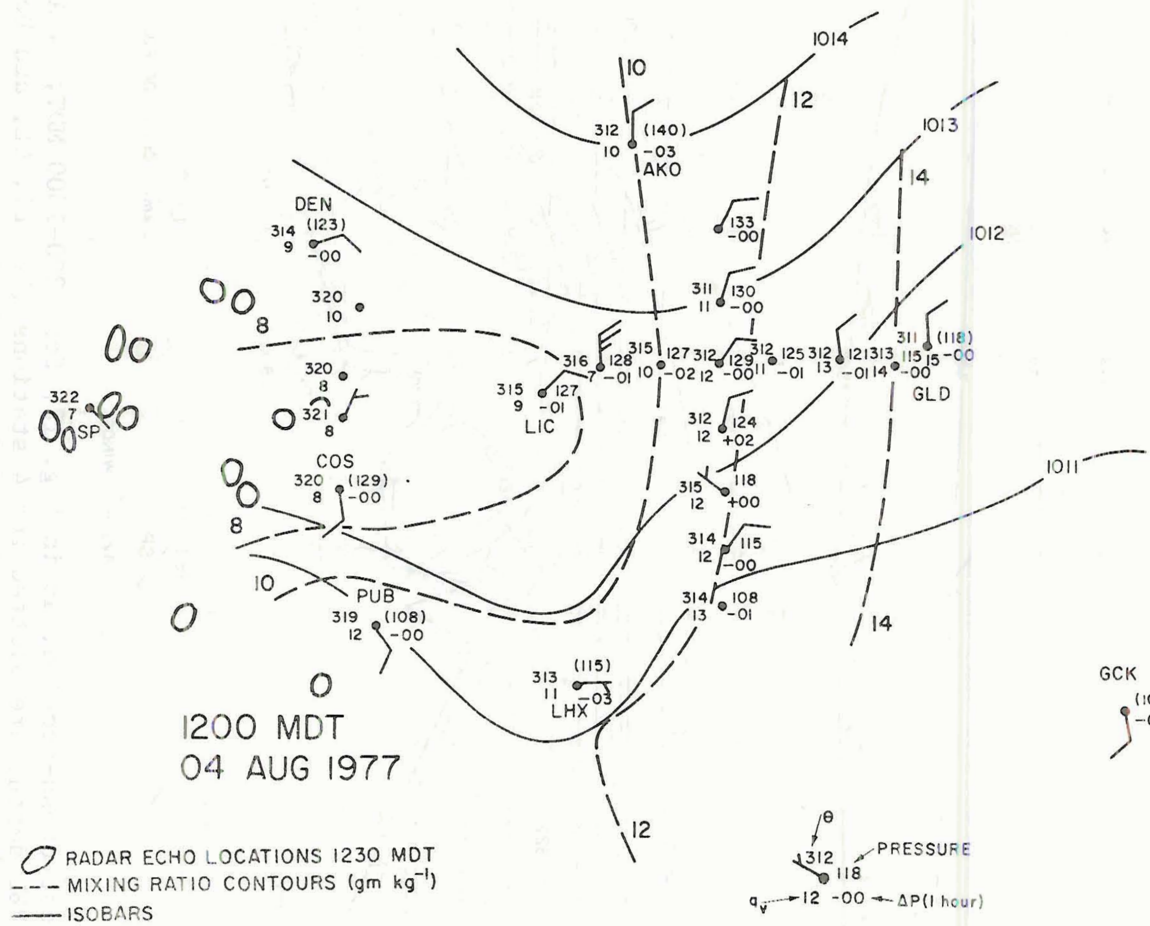


Figure 57. Surface map using SPACE/HIPLEX mesonet data on the High Plains. Surface pressure and surface water vapor mixing ratio are contoured. Limon radar outline and station key are provided.

wind speed with very little directional shear. A dry stable layer to 470 mb lay below a deep moist layer up to 240 mb. This layer showed the influence of deep cumulus convection, which had cooled the area near probable cloud top (at 240 mb) by about 2°C since the 1030 MDT sounding (Fig. 52). Strong stability above 240 mb would indicate that convective clouds probably would not grow much higher than 11 or 12 km over South Park during the afternoon.

Rawinsonde and aircraft data are combined on an east-west cross section in Fig. 56. Soundings from Denver and other NWS rawinsonde stations are also available for this time. On the lower margin of Fig. 56, the average wind speed and direction through the depth of the planetary boundary layer (PBL) is plotted for four rawinsonde stations (SP, DEN, LI, and GL). The PBL depth is here defined as the probable depth to which surface-based thermals could rise, based on an inspection of the plotted soundings.

The average PBL wind plot reveals a substantial amount of divergence being generated at low levels at all stations east of the mountains. This is consistent with the diurnal pattern of divergence observed by Bleeker and Andre (1951). A region of low-level convergence is seen to have existed over the Front Range area at this time. This results from the entrainment of upper level westerly momentum into the deep PBL over the mountains, while the much shallower boundary layer over the plains contained more easterly winds, driven by slope effects and a north-south surface pressure gradient. The region where the two forces converged coincided with the area of initial deep thunderstorm formation.

The pattern of vertical PBL development also reveals marked differences among the sounding locations. Both Denver and Goodland had thin boundary layers (0.8 km), while the Limon PBL was much warmer and deeper (1.6 km). This difference may be due to the location of Limon on the Palmer Lake Divide, while Denver and Goodland are in low-lying areas where deeper stable layers had built up overnight. Convergence of slope winds over the Palmer Lake Divide may have created enough upward vertical motion to counteract the general subsidence field over the plains postulated by Dirks (1969). Cold advection by northerly winds was a probable factor inhibiting PBL growth at Goodland, where the PBL was capped by a sharp $3^{\circ}K$ inversion. This stable layer was analyzed in the cross section (Fig. 56) to intersect the surface between Limon and Goodland in the same fashion as a cold front, and in agreement with surface temperatures (see Fig. 57). The PBL extended to 2.8 km AGL or higher over the Front Range and the Mosquito Range, with the South Park PBL being somewhat cooler and more stable.

The cross-section of water vapor mixing ratio in Fig. 56 shows the effects of mesoscale vertical motion and deep cumulus convection. At upper levels, thunderstorms increased the moisture over South Park, while subsidence greatly decreased the moisture over Goodland. At low levels, however, the highest mixing ratio was at Goodland (15 gm kg^{-1}) with more modest values of 8 gm kg^{-1} at Limon, and still less farther west. At Grand Junction, high humidity in light southwesterly winds continued to supply Pacific moisture into Colorado at 500 mb.

A mesoscale surface map covering the area from South Park to Goodland at 1200 MDT is shown in Fig. 57. Included on this map are data from 8 NWS surface reporting stations, 17 special SPACE/HIPLEX recording surface stations, and the PAM base station in South Park. Raw pressure data from the SPACE/HIPLEX stations were normalized with NWS pressure data in the manner described by Fujita, et al., (1956). Pressure deviations from the mean for this day were computed using the reported altimeter setting at the NWS stations in order to minimize the effects of the rapid temperature changes observed on convective rainfall days. The change in pressure from the previous hour is plotted for each station. Potential temperature, water vapor mixing ratio, and winds are also plotted at each station. Contours of pressure and mixing ratio are drawn. Outlines of the minimum radar echo observed at Limon are drawn with a dark line, taken from the radar summaries which are produced on the half hour (see Danielson and Cotton, eds., 1977); thus, the radar data are valid from 5-30 minutes after the surface data. Comparisons of Limon radar intensities with other radars can be made using Table 1.

The surface data show a coherent east-west moisture gradient extending from Goodland west to the mountains. South of the Palmer Lake Divide, however, a moist tongue extended up the Arkansas valley to the edge of the mountains. The Palmer Lake Divide stood out as an area of higher θ (an elevated heat source) and lower mixing ratio. Radar echoes occurred only over mountainous areas; satellite photos confirm that cumulus convection was still being totally suppressed over the plains.

4.4 4 August 1977 - Formation and Propagation of Early Mountain Thunderstorms

By 1230 MDT, a deep boundary layer existed over South Park, the Front Range, and along the Palmer Lake Divide, with a pattern of low-level convergence and sufficient moisture to sustain deep convection.

In this section, the occurrence of this deep convection during the period of its transition from a group of mountain thundershowers to a large High Plains mesoscale convective system is documented, using radar, rapid-scan satellite, and PAM surface data.

High resolution close-up satellite pictures of the SPACE/HIPLEX area are shown in Fig. 58. These images were created using video imaging of digital brightness data (Phillip, 1979). At 1200 MDT (Fig. 58a), cumulus clouds were forming throughout the foothills and South Park area. The small cells shown in Fig. 57 had just begun to appear on radar.

The 1245 MDT satellite image (Fig. 58b) shows a rapid increase in cloud brightness in an east-west streak passing across the north end of South Park, and a group of bright clouds appearing in the Colorado Springs area. These bright areas correlate well with the locations of growing precipitation echoes in Fig. 59a. The sequence of radar summaries in Fig. 59 was created using the lowest detectable signal at Limon (TRW--) to outline all precipitation regions, and then adding reflectivities, updraft outlines, and echo tops using data from the Limon hourly summaries, NCAR/CP-3 radar, and the first usable data from the CSU 10-cm radar (CBS-4).

Focusing in more closely on South Park, a PAM-CP-3 depiction (Fig. 60) for 1254 MDT shows one member of the east-west line of cells, here designated C1n, at the north end of the Park. This cell had a reflectivity of over 40 dBz, 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

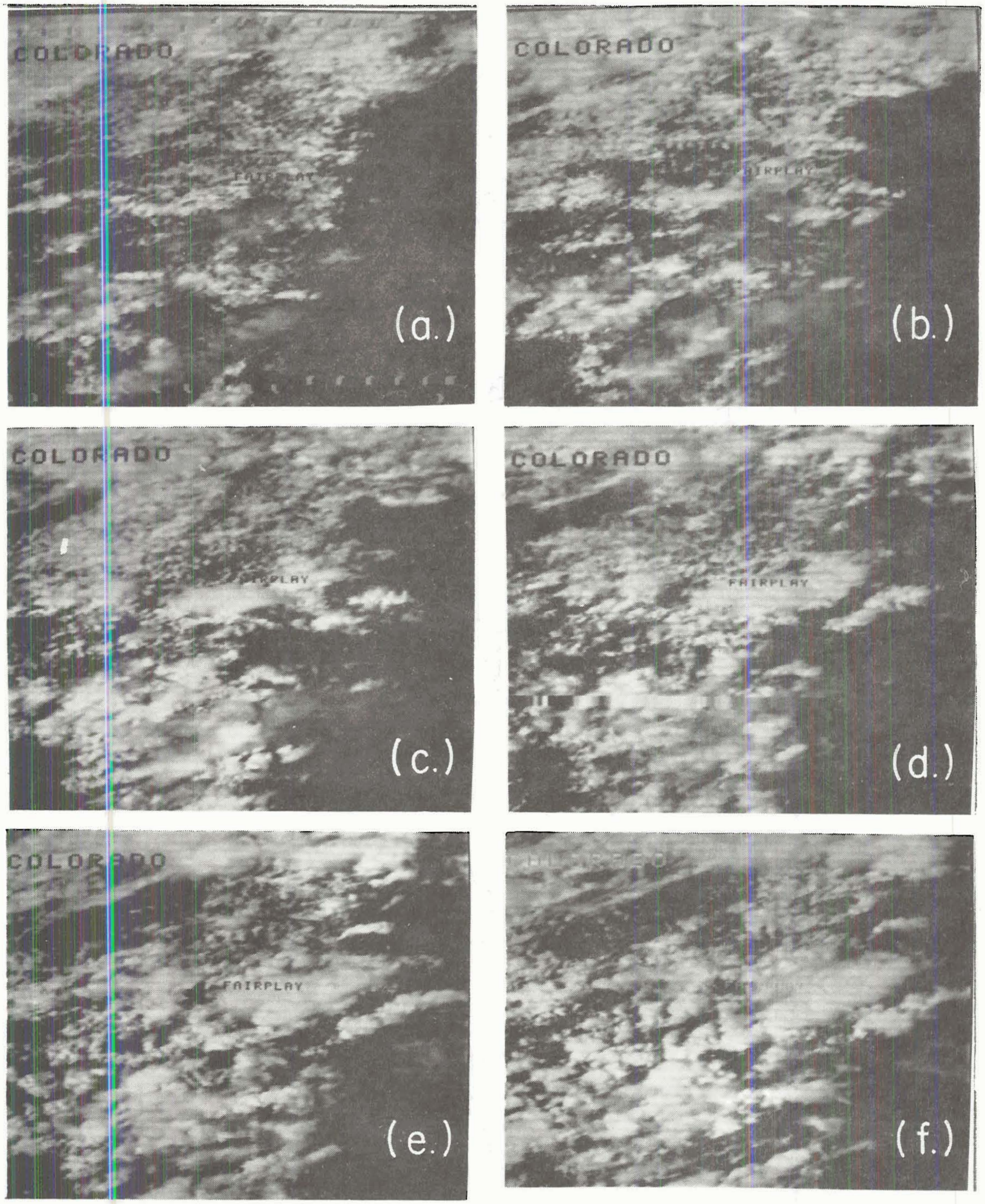


Figure 58. Visible satellite images, processed by video imaging techniques showing eastern 2/3 of Colorado and part of New Mexico. State borders in Fig. a) Town of Fairplay, about 10 km north of CSU base, is labeled. The town is located at the lower left corner of the label. The dark surface feature, lower right of each figure, is the Arkansas River east of Pueblo. The Palmer Lake Divide is marked by clouds, just north of the Arkansas River, especially in Fig. 58b. Picture times are a) 1200 MDT, b) 1245 MDT, c) 1315 MDT, d) 1345 MDT, e) 1415 MDT, and f) 1442 MDT.

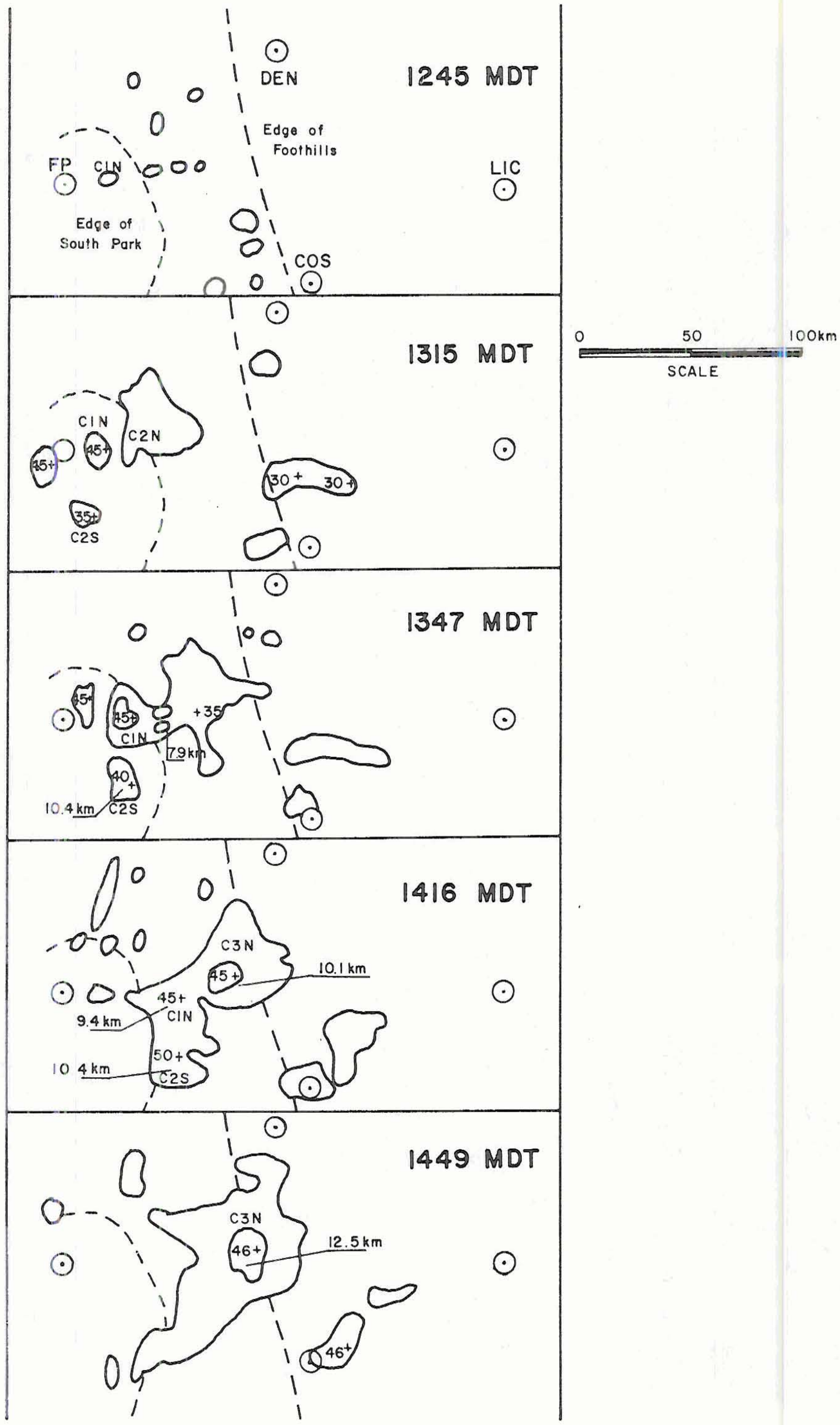


Figure 59. Composite radar summaries from the region between Fairplay (FP) and Limon (LIC), using data from CP-3, CBS-4, and Limon NWS radars. Intensities in dBz, echo tops are in km MSL. Cells referred to in text are labeled. Summary times are a) 1245 MDT, b) 1315 MDT, c) 1347 MDT, d) 1416 MDT, and e) 1444 MDT.

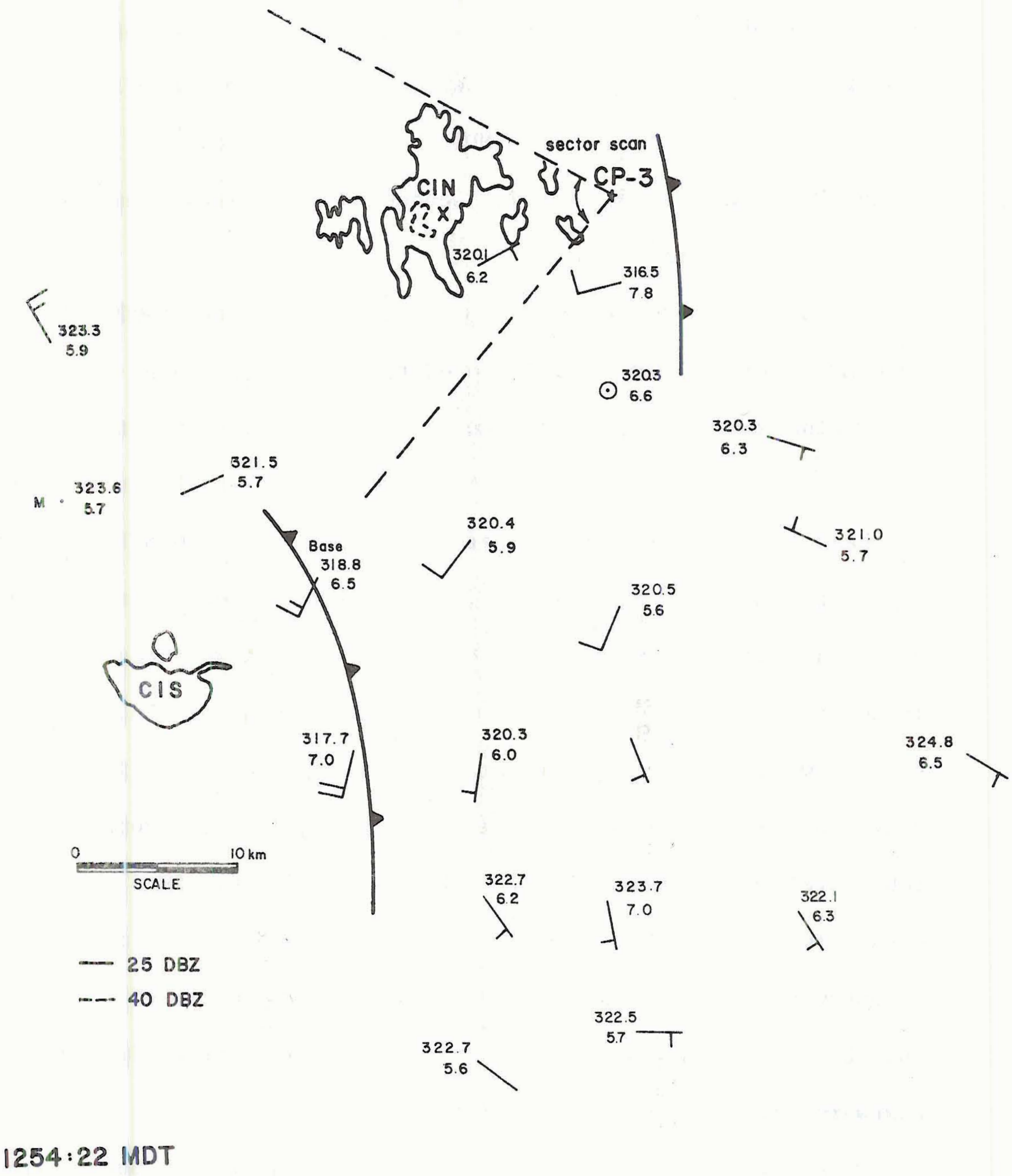


Figure 60. PAM-CP-3 summary, as in Fig. 24, for 1254 MDT, 04 August, 1977.

decreasing, and mixing ratios increasing slightly. Undisturbed areas of southern and eastern South Park showed mostly light southeasterly and easterly winds and warm temperatures ($\theta = 322^{\circ} - 325^{\circ}$), suggesting that a deep, heated boundary layer extended to about 2.8 km AGL over these areas as indicated on the 1301 MDT SP sounding (Fig. 55). Northern areas of the Park had already been influenced by downdrafts from the northern tier of cells by this time.

Cumulonimbus development proceeded rapidly after 1300 MDT. By 1316 MDT (Fig. 61) CP-3 radar showed two large cells near the base, the southernmost one being in the process of splitting into two cells, C1s and C2s, both associated with the downdraft gust-front which passed the base at 1254 MDT (PAM data are unavailable at 1316 MDT, since the PAM system had been disabled by lightning-caused power surges). The combined radar summary for 1315 MDT (Fig. 59b) shows three strong cells in South Park. The northernmost two cells, including C1n, lined up east to west with a rapidly expanding precipitation area in the Front Range northeast of South Park, in a climatologically favored area for echo development (Henz, 1974). Satellite data (Fig. 58c) show an increase in brightness over South Park and the area to the northeast and a southward bulge in the east-west convection line caused by cells C1s and C2s. A line of cells had also formed from Colorado Springs northeastward onto the Palmer Lake Divide.

The nature of the cold outflow behind the cells in South Park is indicated in Fig. 52, for 1336 MDT. Winds at the gust front location were northwesterly, switching to due north farther west of cell C2s. Note the strongly divergent flow between this cell and the decaying

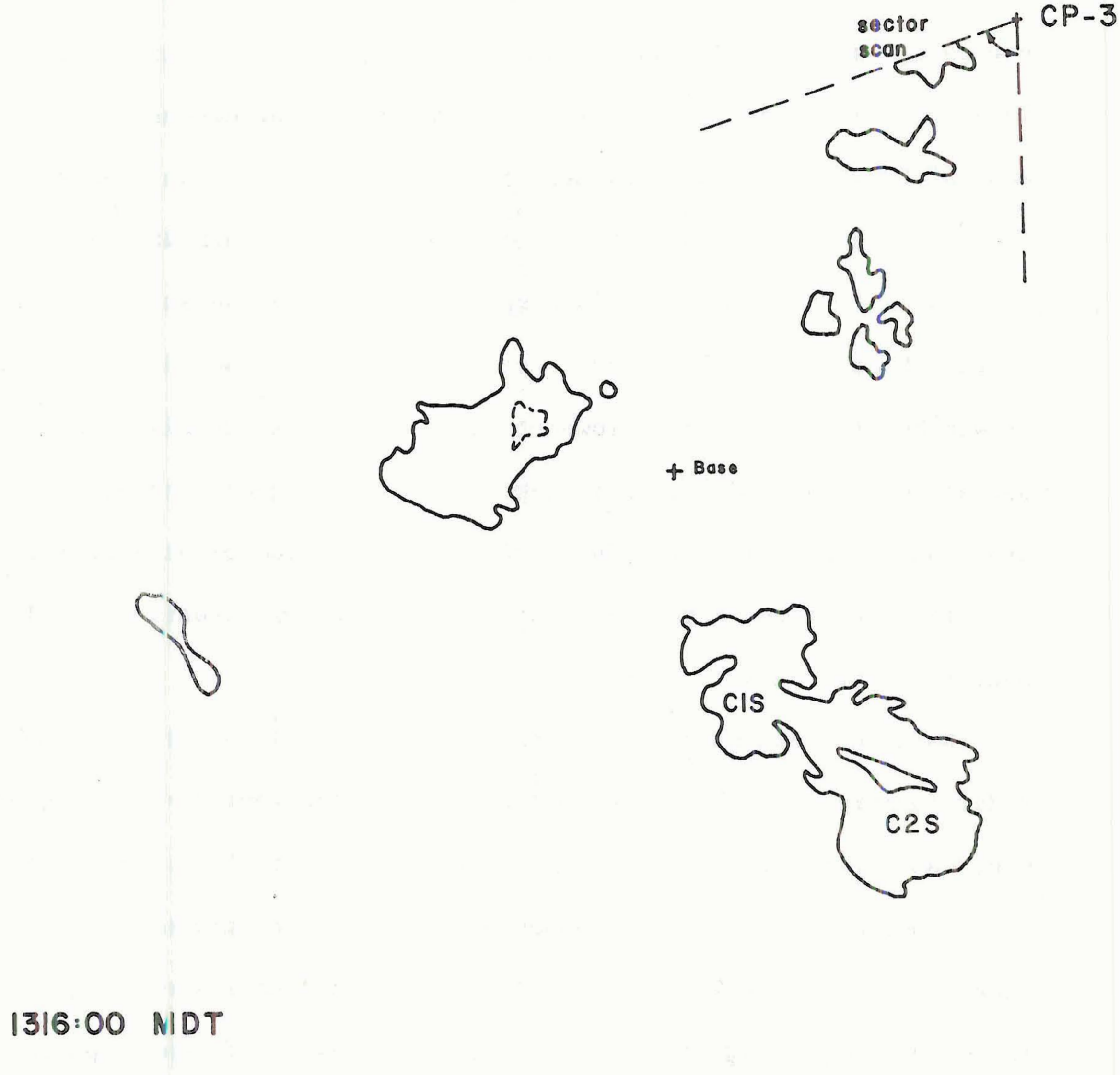


Figure 61. CP-3 radar contour data, on same scale as Fig. 24, and other PAM-CP-3 figures for 1316 MDT, 04 August 1977. Outer bold contour level is 25 dBz, inner bold contour is 40 dBz. (PAM data not available at this time).

cells near the CSU base. This appears as a clearing area on the satellite photo for 1345 MDT (Fig. 58d). Fig. 62 also shows that, while the cells near the base had decayed, cell C1n had intensified, and was the strongest cell in South Park. The importance of this cell is shown on the radar summary for 1347 MDT (Fig. 59c). CBS-4 data indicated that a new cell, labelled C2n, was growing 30 km east of cell C1n within the large echo mass northeast of the Park, while no new echoes were forming east of C2s. Cell C2s propagated in a continuous fashion from a westerly (260^{o}) direction at about 10 m s^{-1} until 1413 MDT, when it began to break up into discrete cells propagating on the northeast edge (Fig. 63). At this time, the cell was over the eastern edge of South Park, with new growth occurring over much lower terrain of the Platte River valley. Surface winds behind this cell were strong, divergent, and very coherent from the north. With clearing skies due to surface divergence (visible on satellite photo, Fig. 58e), surface θ was again increasing rapidly in southern South Park.

North of this strong thunderstorm, and visible on the 1416 MDT radar summary (Fig. 59d), the second cell in the west-to-east sequence, C2n, was located 20 km northeast of the edge of the Park. The third and most important cell of this sequence, cell C3n, had grown and intensified rapidly to over 45 dBz, 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 east-west line of 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

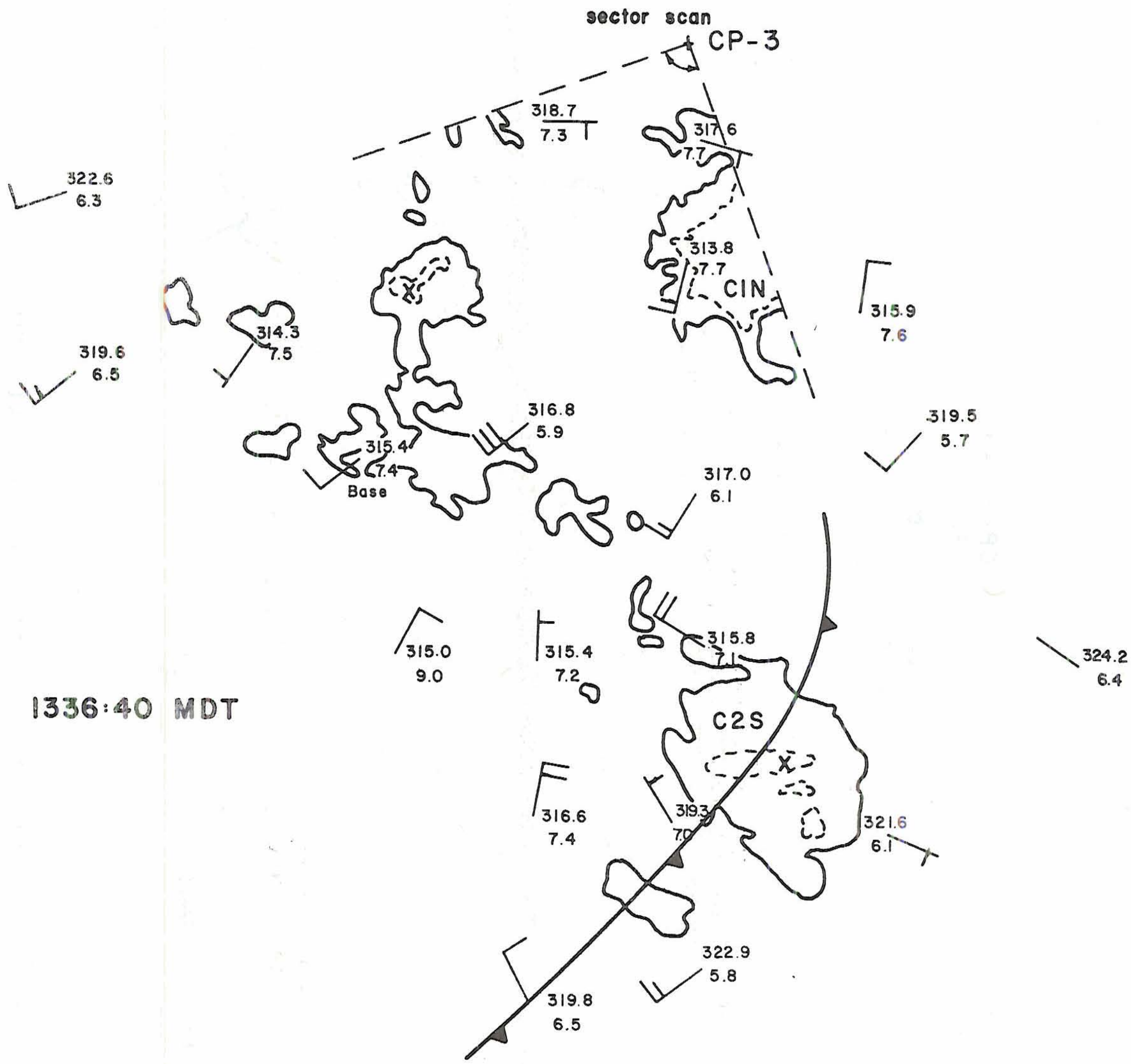


Fig. 62. Same as Fig. 60, for 1336 MDT.

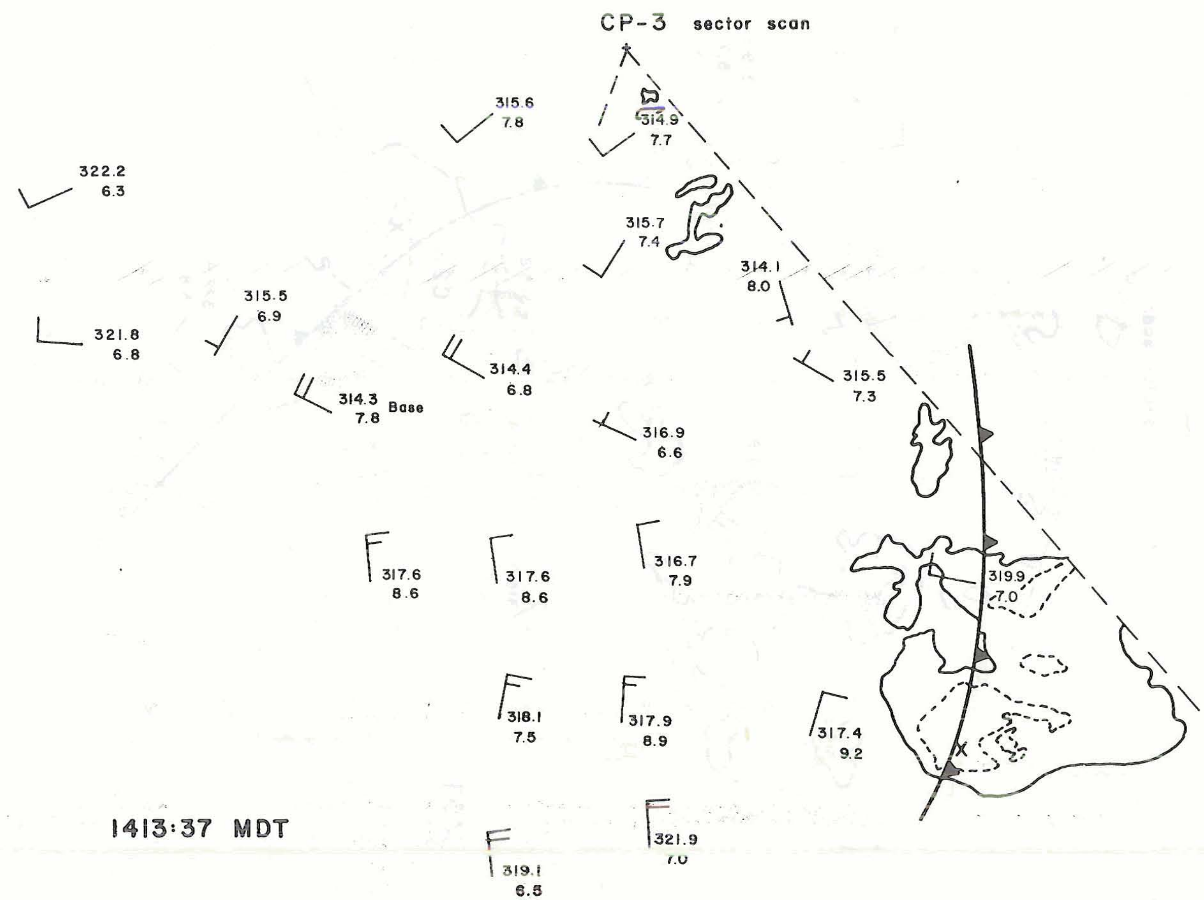


Figure 63. Same as Fig. 60, for 1413 MDT.

South Park, aiding the process of discrete eastward propagation which took place there.

After 1415 MDT, the area of strong cumulonimbus development had shifted completely to the plains - Front Range interface, as shown on satellite pictures (Fig. 58f). South Park radar echoes had dissipated rapidly, with the northern sequence of cells disappearing earliest. The locus of cumulonimbus activity on the Front Range was at cell C3n, the third of our northern sequence of cells. This large storm was the first echo of the day to grow up to near the tropopause (12.5 km or 41,000 feet, as observed by CBS-4 radar). This cell was observed by both radar (Fig. 59e) and satellite (Fig. 58f) to be moving faster than the small, intense cells emanating from the Colorado Springs area.

4.5 4 August 1977 - Evolution of the Intense High Plains Mesocale Storm

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. At about 1500 MDT, rapid growth and intensification of thunderstorms occurred at the western edge of the plains, concentrated on the northern and southern flanks of the Palmer Lake Divide. The balance of this chapter will trace the continued evolution of this mesoscale system for the remainder of August 4.

Surface data at 1500 MDT, when superimposed with the 1530 MDT Limon summary (Fig. 64), show strong easterly inflow into the region of rapid cumulonimbus intensification. The northernmost intense storm, located southeast of Denver, spawned a small tornado at approximately

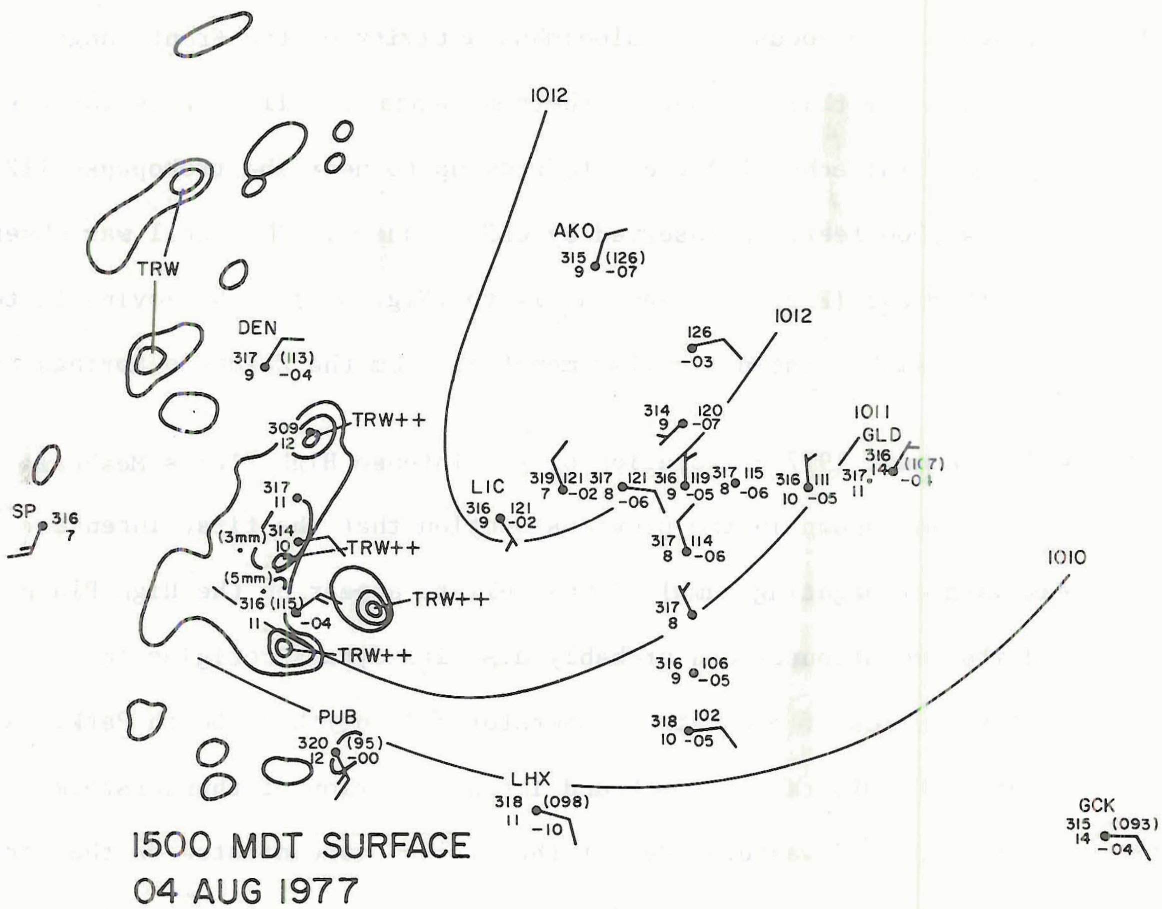


Figure 64. SPACE/HIPLEX surface map, similar to Fig. 57 with mixing ratio contours omitted, for 1500 MDT, 04 August 1977. Thunderstorm intensity designations as in Table 1.

1545 MDT. Surface winds in the Arkansas valley indicated stronger convergence and more low-level moisture (11-12 gm kg^{-1}) to the southeast of the storm area compared to less coherent winds and less surface moisture (7-8 gm kg^{-1}) in the Limon area. The strongest cumulonimbi were subsequently observed to grow in the Arkansas valley. Strong pressure falls, mostly greater than 0.5 mb/hr, continued in eastern Colorado.

After 1530 MDT, a solid mass of thunderstorms, as seen on satellite photos (Fig. 65a,b), proceeded southeastward from the Colorado Springs area. Limon radar resolved this mass into at least four separate storms, each with intensities of over 50 dBz. Surface winds behind this group of cells were strong northerlies, 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.

By 1700 MDT (Fig. 66), the most severe convective cells were located about 50 km due 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. The eastern edge of this echo region extended to 35 km east of Limon. This was confirmed by data from the Goodland HIPLEX radar. The dashed line in Fig. 66 shows the eastern edge of a 20 dBz echo region recorded on Goodland radar B-scans (all vertical levels checked, highest reflectivity reported). 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

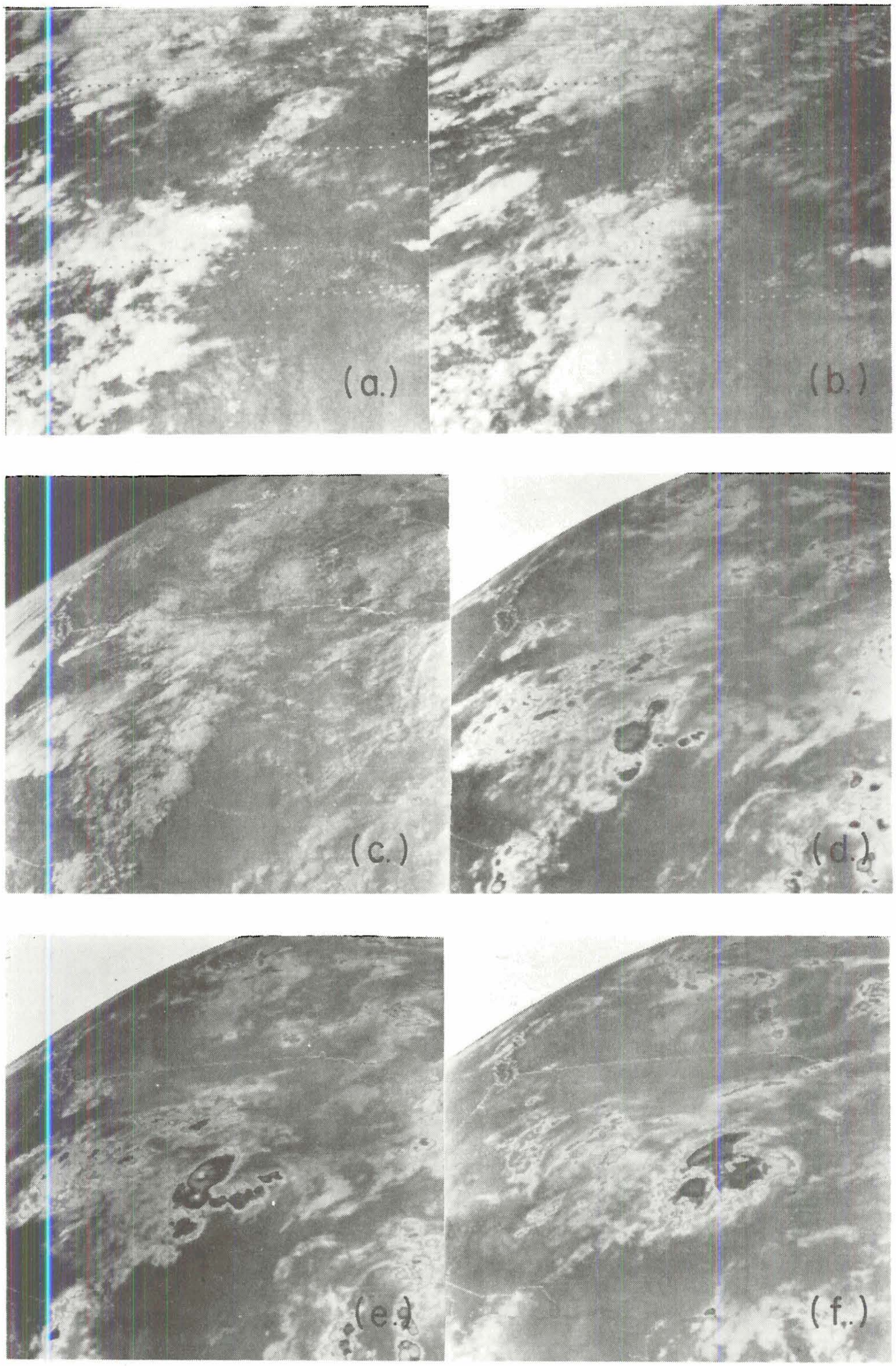


Figure 65. Satellite images of western U.S., on 04 August 1977, for a) 1530 MDT (visible image), b) 2230 MDT (visible), c) 1800 MDT (visible), d) 2100 MDT (infrared image), e) 2230 MDT (IR), and 0500 MDT, 05 August 1977 (IR).

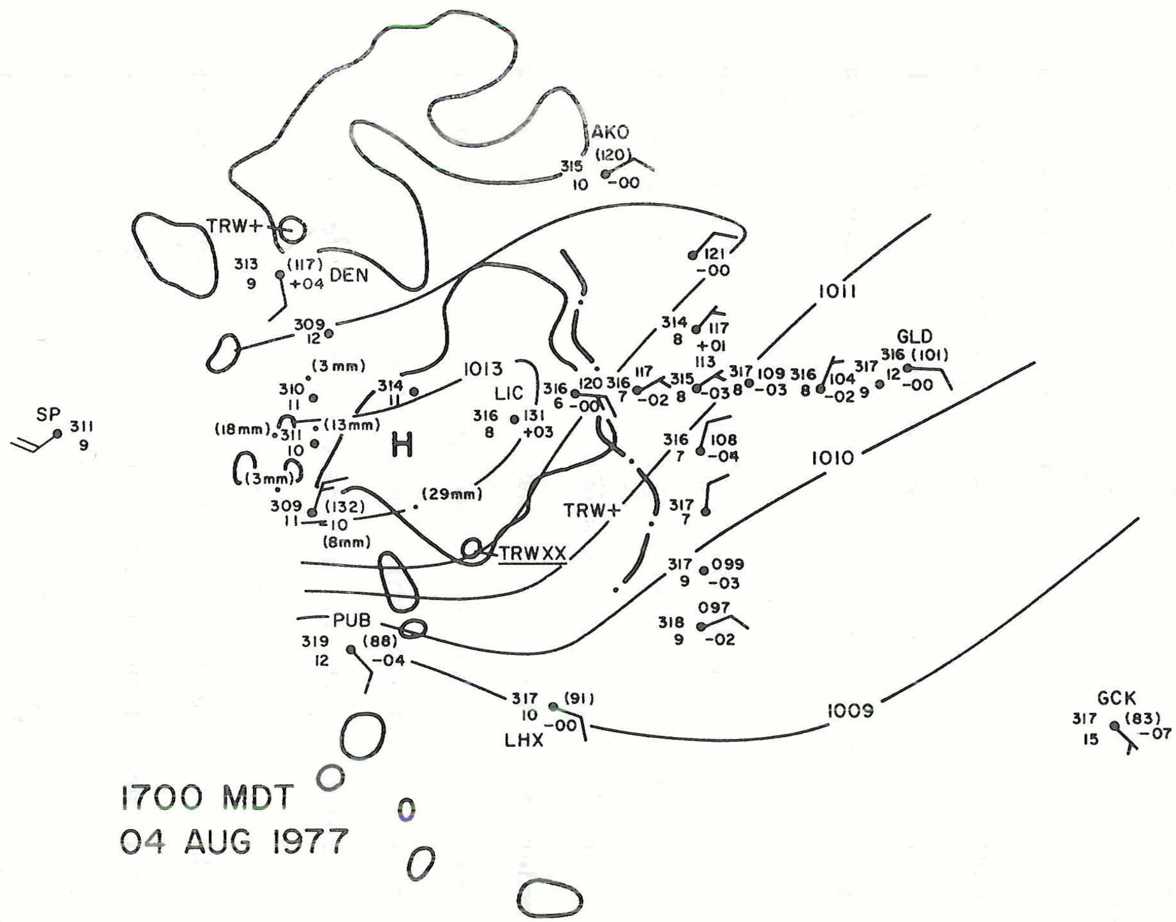


Figure 66. Similar to Fig. 64, for 1700 MDT, 04 August 1977. Bold dashed line is edge of Goodland radar echo.

low enough to enter the Limon radar's very low ($\frac{1}{2}^{o}$) scan. Another heavy thunderstorm northeast of Denver was part of another large echo mass which was separate from the Limon storm but seemed to be propagating in a similar manner. By this time, thunderstorms in the mountains were mostly small and scattered.

Surface winds ahead of the mesoscale convective system were generally easterlies as surface pressures continued to fall. An exception to this was Limon, which had rising pressure in calm winds. The strongest easterly wind, about 7 m s^{-1}, was observed 30 km east of Limon near the edge of the echo overhang. Surface potential temperature ahead of the storm and at Limon were almost uniformly 316^{o}K. Thus, Limon had not yet been affected by storm downdrafts or mesoscale outflow. Stations west of the storm line, such as Colorado Springs (COS) had moderate northerly winds and cool temperatures. Mixing ratios continued to be drier near Limon (6-8 gm kg^{-1}) than in the Arkansas valley or at Goodland, which had 9-12 gm kg^{-1}.

Concurrent with the surface data in Fig. 66, at 1700 MDT, rawinsondes were launched from Limon and Goodland. A skew-T log-P plot of the Limon sounding (Fig. 67) reveals its unusual nature, as it apparently passed through the overhanging raincloud. Except for a slight inversion in the lowest 50 m, the boundary layer was dry-adiabatic up to 620 mb, or 2.5 km AGL. Light easterly (inflow) winds prevailed in the lowest 1.0 km of this, above which the wind was northerly up to 550 mb , well above cloud base. Above this, very light southerly winds extended above 500 mb to a strongly stable layer at 460 mb, above which

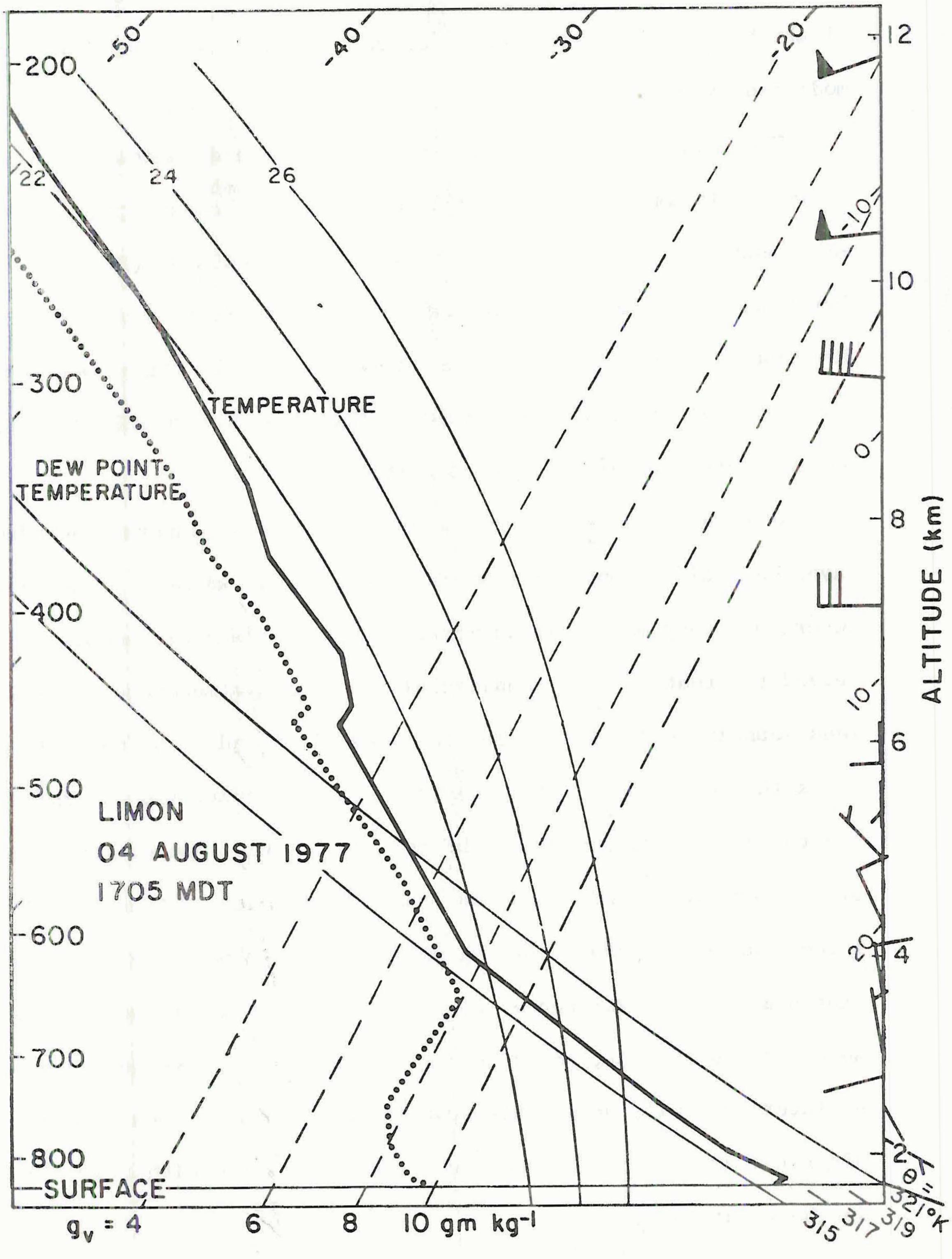


Figure 67. Limon sounding for 1705 MDT, 04 August 1977, plotted on skew-T log-P diagram.

strong westerly winds prevailed. Thus, the part of this balloon flight below 460 mb occurred in an updraft or other region of storm-modified dynamics.

The dominance of storm scale and mesoscale dynamics over the larger scale ambient flow is clearly evident on construction of a mesoscale east-west cross section for 1700 MDT - 1800 MDT (Fig. 68). Soundings from Limon and Goodland at 1700 MDT, South Park and Grand Junction at 1800 MDT, and an east-to-west aircraft flight which passed over Limon at about 1740 MDT (N10UW, flying at 4.7 km MSL, or about 560 mb) were used in this cross section.

At Goodland, ahead of the storm system, the planetary boundary layer was still capped by a sharp inversion 2.2 km AGL. Beneath this inversion, very moist air in moderate easterly and northeasterly flow served to create a very conditionally unstable atmosphere. The Goodland sounding had a Totals Totals index of 58 and a 500 mb Lifted Index (LI) of -4.5°C, both very unstable. However, the inversion at the top of the PBL prevented the release of this instability by means of cumulus convection. The continued maintenance of this inversion through an entire day of strong solar heat flux into the PBL suggests that some outside influence, possibly mesoscale subsidence or cold advection in the PBL, acted during the day to suppress deep convection. As later data will show, this suppressed instability was released only after the arrival of a mesoscale convective system with its origins in the Front Range area.

The contrast between the Limon and Goodland soundings on the cross section in Fig. 68 reveals the strong gradients in temperature, moisture, and vertical structure which existed over eastern Colorado at this time.

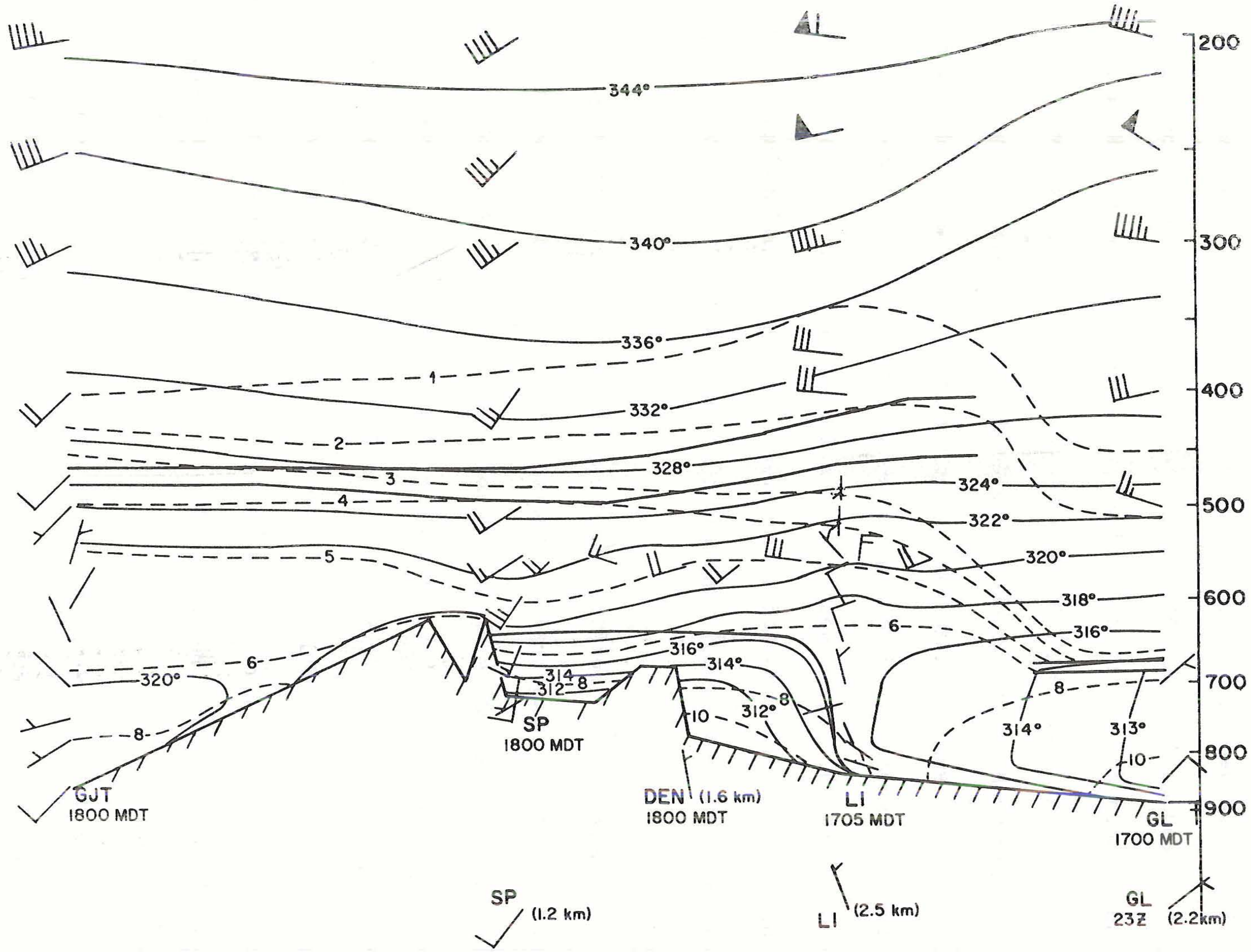


Figure 68. Same as Fig. 56, for 1700-1800 MDT, 04 August 1977. Aircraft flew east to west.

In the lowest 2 km, a potential temperature gradient of over $3^{o}K$ existed between Limon and Goodland. Thus, the easterly and northeasterly winds observed in this layer should have created a substantial amount of cold advection, perhaps enough to maintain the 690 mb inversion which suppressed convection at Goodland. Between 700 mb and 500 mb, a strong moisture gradient existed between the moist cloud layer over Limon and the much drier air above the Goodland inversion. Aircraft data from this layer suggest that the northerly cloud layer winds observed at Limon existed only in a band extending 50 km or less from east to west. Above 460 mb, latent heat released in deep cumulus clouds at Limon and farther west created substantial warming of the atmosphere, resulting in a strong horizontal gradient of potential temperature between Limon and Goodland.

Cold, stable outflow air occupied the region to the west of Limon at 1700 MDT. This region is bounded by a bold line on the cross-section (Fig. 68), extending up to 660 mb, the top of a surface based inversion observed at South Park. Aircraft vertical motion measurements indicate coherent subsidence extending from South Park to Limon, with the strongest subsidence being near Limon, just west of the northerly wind area at 560 mb. Averaged PBL winds, plotted on Fig. 67, show mean northerly winds at Limon and Denver, with a convergent area between Goodland and Limon.

The rapid apparent motion of the convective squall line can be seen by comparing surface and radar observations from 1800 MDT (Fig. 69) with data from one hour earlier (Fig. 66). The echo front east of Limon had moved eastward at 15 m s^{-1} during this time. All stations

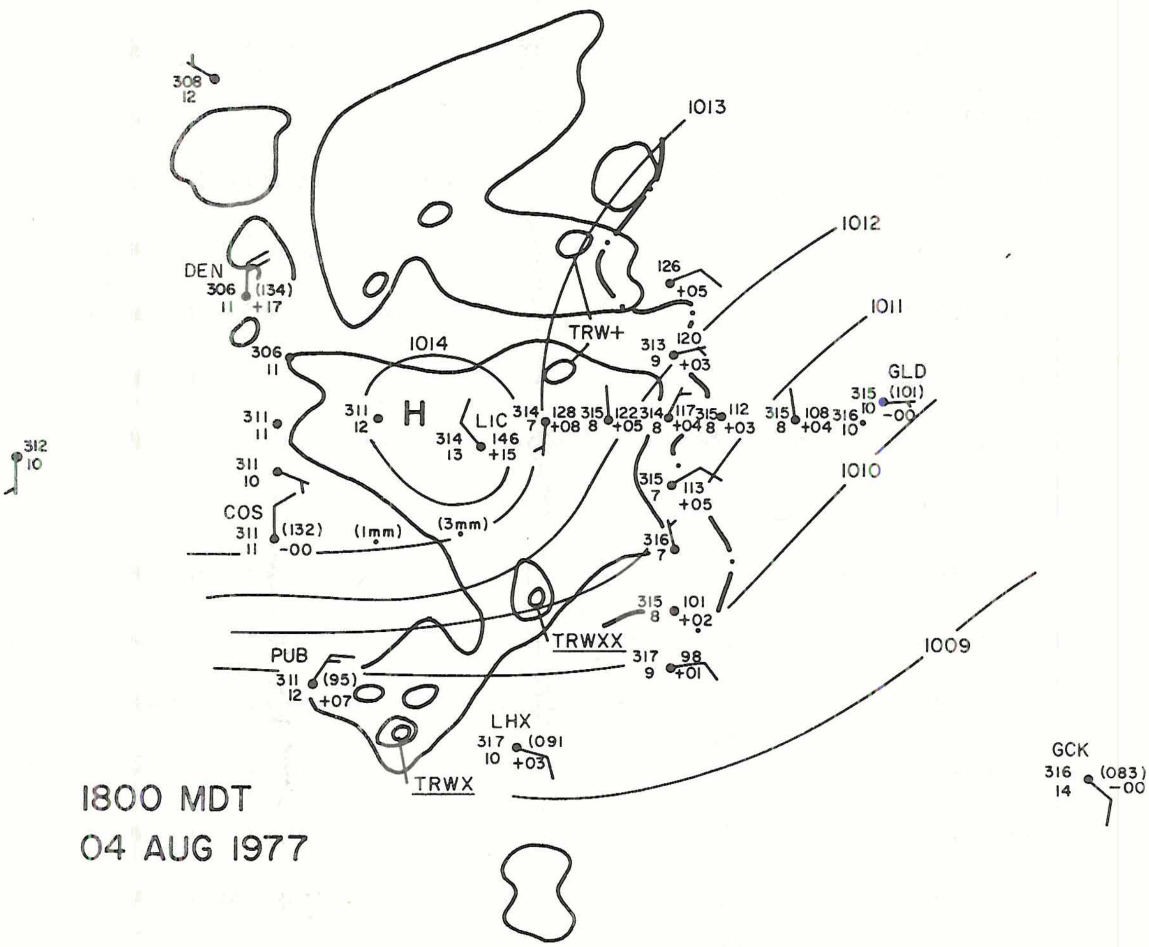


Figure 69. Same as Fig. 66, for 1800 MDT, 04 August 1977.

in eastern Colorado reported pressure beginning to rise, with the largest one hour rises occurring 50-90 km behind the echo front. Potential temperatures decreased 1-2^{o}K at all stations. This indicates that the surface was cooling due to overcast skies over the mesonet, but no penetrating downdrafts had yet reached the surface east of Limon. 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 in the area east of Limon was only 3-5 mm. Thus, a coherent, eastward propagating squall line was able to maintain itself without a region of strong precipitating downdrafts. However, a region of increased surface pressure, or mesoscale high, did exist behind this storm system. A similar lightly precipitating storm system was moving on a parellel course about 50 km north of the Limon system.

In contrast, deep, intense, heavily precipitating thunderstorms were associated with the squall line in the Arkansas valley, 50 to 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. Both the intense and the moderate storm systems were part of a north-south line of mesoscale convective systems extending almost from Canada to Mexico, as seen on satellite photos (Fig. 65c). The most intense storms of the entire line were those located in the Arkansas valley of Colorado. By 2100 MDT (Fig. 65d), however, a line of intense convective activity had appeared in an area near the Colorado-Kansas border extending north from Goodland. Surface data throughout the day had shown a strong west-to-east moisture gradient in this region, with surface mixing ratios of 7-8 gm kg^{-1} to the west and 14-15 gm kg^{-1} to the east of this area. Radar data document the migration of a 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 MDT, this sytem began to intensify as it encountered enhanced low-level moisture and formed a very coherent line of intense thunderstorms. By 2100 MDT (Fig. 70), this line was approaching Goodland, bringing severe weather with reflectivities of over 60 dBz and echo tops of at least 15.5 km (51,000 ft). A region of coherent northerly winds in cold, moist air extended at least 100 miles west from the thunderstorm line, repeating the pattern of northerly outflow winds behind convective regions, seen in South Park and the Front Range earlier in the day.

Infrared satellite data (Fig. 65d,e) confirm the rapid intensification of the relatively narrow north-south line of storms near Goodland at 2100 MDT (Fig. 65d) into the dominant system on the plains by 2230 MDT (Fig. 65e), with a simultaneous decrease in intensity of the Arkansas valley storms. The northern system produced approximately 50 mm of precipitation over a large region of northwestern Kansas. This was about 15% of the summer seasonal mean in this dryland farming region. By 0530 MDT on August 5, 1977, a large area of nocturnal storms covered eastern Kansas and parts of Missouri (Fig. 65f). This was the third consecutive night of nocturnal storms in the same general region, an area with a climatological maximum of precipitation occurring at night in the summer.

4.6 4 August 1977 - Summary

The pattern of convective activity which evolved on August 4 closely duplicates many of the previously observed climatological mean

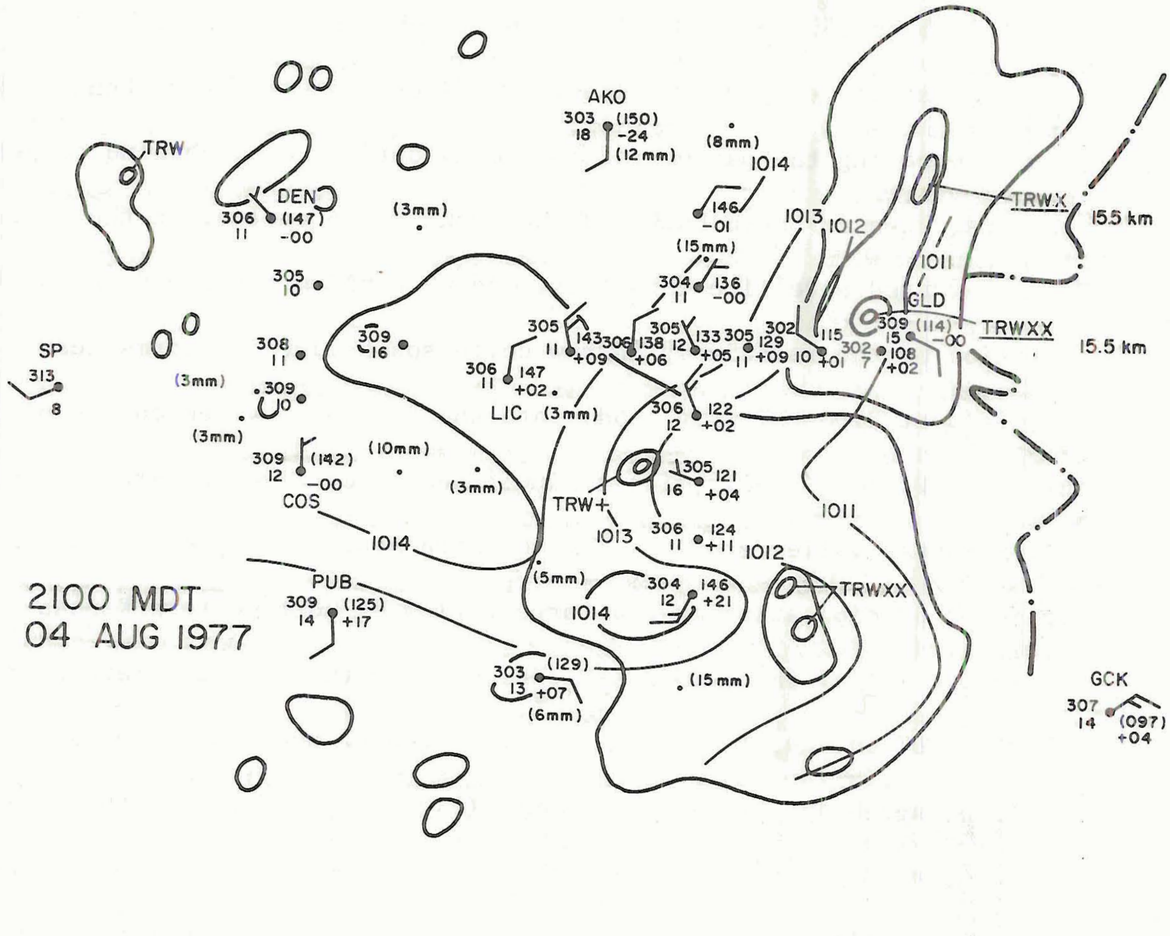


Figure 70. Same as Fig. 66, for 2100 MDT, 04 August 1977.

patterns put forth in chapter 2. Included among these patterns are the growth of first cumulus clouds over the highest peaks, the formation of precipitating cells over certain "hot spots", discrete propagation of mountain thunderstorms eastward with the mean winds, preference of early storm development for the Palmer Lake Divide area, intensification of the mesoscale storms as they passed into regions of greater low-level moisture, and widespread nocturnal showers in the central Great Plains. August 4 was the second of a series of eight consecutive days on which mesoscale convective storms formed on the High Plains and moved eastward through the nocturnal storm region. Many of these were observed to maintain their identities for several days as they traveled across the U.S. and out into the Atlantic Ocean.

Several synoptic-scale factors appeared to contribute to the creation of an environment suitable for eastward mesoscale propagation on August 4. Colorado was located at the northern edge of a 500 mb subtropical high pressure center, such that winds were moderate westerlies containing substantial Pacific moisture at 500 mb. East of the Rockies, low level Gulf moisture was present as far west as South Park, having been advected up from the plains by slope winds on the afternoon of August 3. Over the High Plains, cool northerly winds, possibly created by circulation around the previous day's mesoscale storm, helped inhibit boundary layer growth and suppress convection, while at the same time containing enough moisture to support deep thunderstorms once the mesoscale forcing from the west triggered storm formation. The presence of diurnal precipitation patterns in the long-term climatological data indicates that synoptic conditions which allow thermally driven convective patterns to predominate occur quite often during the summer.

A brief time sequence of events will help point out the most significant findings of this case study. The first phase shows the evolution of the morning boundary layer over South Park. Shortly after sunrise, very small scale slope winds began in the lowest 50 m or less of the atmosphere. After two hours, a larger scale valley wind commenced in the South Platte valley. This created cool, moist advection at the CSU base and other up-valley locations. 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 heated PBL induced cumulus cloud formation by 1000 MDT. These small cumuli acted to eliminate the upper inversion at 480 mb, 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 MDT, in association with a westerly surface gust front. 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 MDT, creating a tornado.

The third phase commenced as this mesoscale squall line began to propagate southeastward 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 than the Arkansas valley to the south. The entire line maintained its linear shape and continued to move rapidly eastward, however. Thus, most of northeastern Colorado, despite being crossed by a mesoscale squall line, received very little moisture, a common result in this semi-arid region. At about 1900 MDT, a related squall line to the north rapidly intensified to severe levels as it encountered greater low-level moisture near Goodland. Previous to this squall line passage, convection in the Goodland area had been suppressed, probably by diurnal patterns of slope winds, cold advection and possibly PBL oscillations, in a manner similar to the suppression of cumulus development over South Park in the morning. The Goodland storms produced 50 mm of precipitation over a large area before continuing eastward to form a nocturnal storm system over the central plains.

5.0 Summary and Conclusions

In this thesis, we have performed detailed case studies of two contrasting days, using a multitude of data sources from the SPACE/HIPLEX 1977 field program. On both days, severe mesoscale convective storm systems formed in or near the central Colorado mountains. On July 19, 1977, a coherent quasi-stationary line of convective storms formed in South Park and remained there throughout its lifetime, while little convective activity occurred on the plains to the east. In contrast, on August 4, 1977, thunderstorms which formed early in the day over the Rockies tended to propagate eastward onto the High Plains, forming a traveling mesoscale squall line which moved across the dry plains of eastern Colorado and into Kansas. The case of August 4 fits the pattern of diurnal terrain-induced convection which was developed in Chapter 2. This is also the case which has a greater societal impact, since the mesoscale storms traveled across an agricultural area which depends on very marginal summertime precipitation for crop production.

In this chapter, we will present a conceptual model which relates most of the terrain effects of Chapter 2 to a case of eastward-propagating mesoscale storms such as August 4. Then we will review and discuss the most important conclusions to be drawn from both case studies. Finally, we will suggest what further research and analysis using the SPACE data might be expected to yield, as well as the form of future field projects relating to these problems.

5.1 Conceptual Model of Eastward Propagating Orogenic Mesoscale Systems

The observations taken on August 4, 1977 and similar days of eastward mesoscale propagation can be used to construct a chronology of events, into which the various scales of motion and the terrain-induced flow patterns that occur on these scales, as discussed in Chapter 2, can be integrated. The chronology can be divided into three basic phases. The first phase lasts from before sunrise until the first radar echoes from mountain thunderstorms appear, usually at about 11-1200 MDT. The second phase then continues until the first mesoscale convective systems appear on the western plains, usually late in the afternoon. The third phase then follows these large systems into the night, until they merge with the late-night precipitation zone in the central plains.

The morning phase begins before sunrise, when the atmosphere over the mountains is most stable. Nocturnal drainage of cool air acts to transfer static stability away from the peaks and ridges into the valleys and nearby plains. After sunrise, a very thin heated PBL forms below the inversion. Winds in this layer are light and tend to go up any local slope. As the depth of the PBL increases, more coherent valley winds develop, typically 2-3 hours after sunrise. These valley winds tend to increase stability by advecting the cooler air upslope at low levels. At the same time, slope and valley winds begin to create mass and moisture convergence over the peaks and ridges. The large heat flux coming from the steep slopes, heating the thinner, less stable boundary layer over those slopes, creates a large buoyancy flux which also serves to induce formation of the first cumulus clouds, usually 3-5 hours after sunrise. As the valleys and elevated plains continue to warm up, a deep, unstable boundary layer is formed, allowing widespread cumulus development. These cumulus clouds act to eliminate the upper inversion, which is often present at about 450 mb. Clouds which penetrate this inversion are then deep and long-lived enough to form precipitation echoes, usually at about 1200 MDT.

The second phase commences as the first precipitating cells appear, over both the highest peaks and over certain lower slopes which induce favorable mass and moisture advection ("hot spots"). These cells extend into the middle troposphere, where stronger westerly winds prevail. These winds cause the cells to translate and propagate eastward. Some cells quickly dissipate as they move into the subsidence area of the slope circulation, or over a stable, less mature PBL. Precipitating downdraft areas begin to form, creating a meso-high due to more dense rain chilled air and carrying westerly momentum from aloft down to the surface, creating a westerly gust "downdraft front", which may gain energy as it flows down hill.

Upslope winds continue to develop and grow stronger over cloud-free areas in the deepening PBL during the afternoon. The intersection of this flow with the thunderstorm gust front or density current may create a zone of intense low-level convergence ahead of the propagating storm system, which would serve as an area for new cell development. As the storm systems move down to the eastern edge of the Rockies, they grow more intense, due to the greater amounts of low-level moisture available on the plains. Thunderstorms and convective systems may tend to dissipate in the lee of the large-scale slope circulation of the Front Range, but some systems find favorable areas for growth and propagation over the Cheyenne Ridge and the Palmer Lake Divide, perhaps merging with already existing convective clusters in those regions.

The development of major mesoscale convective systems on the plains, usually at 1600-1800 MDT, begins the third phase of our chronology. These storm systems can create convective eddies far larger than the thinner PBL of the plains (1.5-2.0 km deep) could generate by itself. Thus, the conditional instability which had been suppressed during the day could then be released. These larger systems create large-scale downdrafts and meso-high pressure areas as well as bringing more westerly momentum down to enhance convergence and propagation at low levels. Eastward moving systems would intensify as they passed through dry lines or other mositure gradient zones, into the humid region of the midwestern U.S.

Diurnal oscillations of the PBL may create a general, low-level convergence zone over eastern Colorado in the late afternoon. Around sunset, the boundary layer quickly stabilizes, creating acceleration of the southerly PBL winds. These strong winds create increased advection of Gulf moisture and perhaps also increased convergence ahead of the traveling storm. The degree to which the various factors promoting low-level convergence coincide in time may determine the longevity and vigor of the mesoscale storm system. The pattern of the low-level jet, interacting with the eastward moving mesoscale system gust fronts, creates low-level convergence and a favorable wind shear environment for deep storms over a large area of the central plains. These storms tend to form and propagate near the weak east-west oriented stationary front which is often a persistent feature of the central U.S. in summer. The large complex of nocturnal storms creates a traveling zone of convergence which resembles a synoptic short-wave. This disturbance can continue to move eastward for several days, reintensifying in the late afternoon each day.

5.2 Significant Results of Case Studies

Under the broad category of "mesoscale convection over mountainous terrain", we have investigated boundary layer and convective activity on a wide range of spatial and temporal scales, ranging from less than a kilometer to 500 km or more, and from a few minutes to more than one day. Using only two case study days, it is, of course, not possible to draw conclusions of a fundamental nature about diurnal phenomena. However, the highly detailed data herein presented, along with other data too voluminous to include, strongly suggest certain physical interpretations, most of which relate to thermal forcing of the atmosphere through heat exchange at the surface. In this section, we will present the most significant physical insights we have gained in the process of these analyses.

Since the environment over South Park on July 19, 1977 was dominated by large-scale "monsoonal" southerly forcing, we might expect most diurnal effects related to thermal winds to have been obscured by larger-scale flow. However, this was not necessarily the case. The first precipitating thunderstorms observable by radar formed at practically the same time (1230 MDT) as on most other thunderstorm days. Also, the location of the first precipitating cumulus cells coincided with the climatological "hot spots" observed by Huggins (1975). This lends support to the statement by Henz (1974) that "hot spots" use thermal slope forcing to perturb the mean flow and create local convergence areas, which in turn generate deep cumulus clouds.

The generation of strong mesoscale flow patterns by a larger-scale mountain-plains thermal contrast seemed to be of overwhelming importance on July 19. Since cumulus development over the flat areas of South Park was delayed until late in the afternoon, extreme surface heating created a meso-low pressure area over South Park. This was sufficient to create easterly inflow from the plains as well as aiding the advection of moist air from the west into the Park. This meso-low provided the initial organization of the mesoscale convective line which subsequently developed. On a larger scale, early storm activity over the mountains to the north apparently created a strong contrast with the heated plains, producing a surface pressure gradient which drove strong northerly winds along the eastern slopes of the Front Range and into South Park. These low-level forcing patterns also emphasized the role of the Colorado Rockies as a barrier to rapid horizontal mixing of contrasting air masses.

The generation of strong northerly winds at the surface despite southerly large-scale ambient winds may also have been related to a mesoscale gravity current, of the kind often observed in tropical regions. The July 19 case study includes detailed observations of a mesoscale squall line which propagated discretely in an upwind direction. While this phenomenon may not be directly related to terrain effects, the occurrence of this event in the center of South Park, within the area of intensive data gathering by the SPACE program, was related to the role of South Park in storm organization previously mentioned. From the standpoint of research operations, the choice of South Park as a location for triple Doppler radar, PAM, and other intensive observational equipment was strongly justified by the volume and quality of data taken on July 19. Further insight into the density current and other storm-mesoscale interactions should be provided by the triple-Doppler studies of Knupp (1979).

The case study of August 4 suggests physical interpretations on a much larger range of scales, due to the less disturbed environment on that day. On a synoptic scale, the conditions under which eastward propagating mesoscale systems formed serve as a useful starting point for more detailed synoptic studies. Among these conditions are moderate westerly flow at 500 mb, advection of Pacific moisture in the layer from 700-500 mb, and the presence of substantial Gulf moisture at low levels in eastern Colorado.

The most important concept to emerge from the study of the South Park boundary layer evolution on August 4 was the role of weak slope winds in suppressing PBL growth, vertical mixing, and cumulus cloud formation over the flat Park. This concept seems to be analogous to large-scale suppression of cumulus activity over the western plains, which occurs over a larger space and time scale. Inhibited vertical mixing would seem to have significant implications for studies of diffusion and convective fluxes in mountainous terrain.

On August 4, the first significant cumulus clouds occurred as a result of excess buoyancy generation over the high ridge of the Mosquito Range. The moisture for these clouds was advected over relatively short distances by slope winds - probably less than 20 km. Thus, the initial environment in South Park and the nearby mountains largely controls the timing of first cumulus formation.

An important objective of SPACE 1977 was to observe the eastward propagation of mountain thunderstorms which subsequently contribute to the formation of large mesoscale convective systems over the High Plains. The CSU 10 cm radar (CBS-4) was intended as the principal tool with which to make these observations. Although performance and data quality of the CBS-4 radar were less than optimal on August 4, the data agreed well enough with Limon radar and satellite data that they were included in the case study. An apparent case of eastward discretely propagating mountain thunderstorms, consistent with the mechanism proposed by Erbes (1978), was observed by this radar. This case may have great significance to possible future weather modification hypotheses. These showers were precursors of a very large, rain-producing mesoscale convective system.

A substantial amount of low-level divergence was generated in the plains during the day on August 4. The growth of the boundary layer was inhibited by a combination of initial stability, cool advection, and subsidence. This resulted in suppression of small cumulus formation and the buildup of the instability which was later released by the mesoscale squall line. This pattern of cloud formation is a very common occurrence in summer, lending support to the concept that the pattern of low-level divergence observed on August 4 is produced by diurnal heating effects. Wind observations were also consistent with diurnal oscillations previously observed by Dirks (1969) and others.

The large linear squall line which passed through eastern Colorado on August 4 retained its north-south orientation despite the existence of strong north-south gradients of moisture in eastern Colorado. Different sectors of the line had radically different intensities of convection and rainfall, yet the speed of propagation was roughly uniform. This would indicate that the dynamic organization for the squall line may have come from a scale larger than the storm.

The mechanism of storm propagation on August 4 was in some ways similar to that observed on July 19. A surface high pressure center, caused by cool, subsiding air behind the squall line, apparently contributed to the generation of low-level convergence ahead of the line. This served to propagate the line eastward despite the lack of a strong westerly "gust front".

In contrast with the case of July 19, however, the low-level convergence was generated on the downshear side of the storm on August 4. This created a rapidly moving mesoscale system on August 4, contrasting with the almost stationary system of July 19.

5.3 Suggestions for Future Analysis of SPACE Data

In the development of the case studies presented in this thesis we have tried to use as many of the South Park data sources as was feasible. However, as of this writing (May 1979) much potentially valuable analysis remains to be done, both on the case days and on other days. Possible analysis efforts which could yield results pertaining to the questions brought up in these case studies are here suggested.

Banta and Cotton (1979) have already published case studies of boundary layer evolution on dry, suppressed days, using the BLP and PAM surface data. Use of PAM data is presently restricted by the lack of adequate computer software for analysis and display of the data. With a modest programming effort, however, PAM data as well as micrometeorological tower and acoustic sounder data should become readily accessible. A more detailed description of bounday layer evolution should then be undertaken. A day with modest, westerly upper winds such as August 4 would show very fine detail about the timing and direction of initial upslope winds. The various local terrain features present at each of the 20 PAM sites would provide numerous examples of various terrain effects. Vertical data from the micrometeorological towers, BLP, and acoustic sounders could be used to guage the lapse rate and the magnitude of the cool upslope advection term. This might also help in the formulation of a surface energy budget. An interesting application of these data would be to estimate the vertical mixing and air pollution dispersion potential at low levels.

Enough data may exist to directly deduce the origin of the parcels which form the first cumulus clouds. BLP, PAM, and possibly powered aircraft data could determine various parameters of the inhomogeneous boundary layer which could be compared with LIDAR data and stereo photogrammetry on the dimensions of the first cumulus clouds (cloud base, etc.) as well as in-cloud parameters measured by the sailplane. On a larger scale, more detailed PAM analysis for mesoscale storms occurring within South Park, including pressure data (not available for these case studies) may help establish the role of orogenic meso-low pressure centers and storm-generated meso-high pressure areas in the formation and propagation of these storms.

A very significant goal of the SPACE 1977 experiment which was not adequately resolved in the August 4 case is the observation of eastward translating and propagating storms as they make the transition from South Park to High Plains system. This task was basically assigned to the CBS-4 (FPS-18) radar, which did not perform well on August 4, it's first full day of operation. Similar eastward propagation days such as August 8 and August 10 should have much better CBS-4 data. An important reason to conduct analyses on these days is to confirm the proper operation of the radar and establish the credibility of its data, since this radar has not been back to the field in the intervening time.

Analysis of data from the mesonet of surface stations between Limon and Goodland should be extended to include time series analysis of individual station data, in the manner described by Fujita et al. (1956). This will give a better depiction of gust fronts and meso-high pressure areas. These data could also be used to determine diurnal patterns of surface pressure and divergence, and possible east-west gradients thereof. The results could be compared with analyses from the National Hail Research Experiment (NHRE) surface mesonet, which was deployed in northeastern Colorado on a similar scale at a similar distance from the mountains.

The rawinsonde data set from SPACE/HIPLEX in 1977 as well as the South Park soundings from previous years represent a largely untapped resource. It should be possible to determine average daily heat fluxes into the boundary layer and other factors relating to PBL evolution by examining the time sequence of soundings at each station. Modification of the environment by cumulus clouds, such as the elimination of the upper inversion discussed in Ch. 2 and Ch. 4, should be observable on most days over South Park. Averaged soundings from undisturbed days on the High Plains should be examined for evidence of the PBL oscillation discussed also in Ch. 2.

5.4 Suggestions for Future Field Programs

While the design of future field studies should hinge on results of the maximum possible analysis and modeling studies of the 1977 data set, some guidelines for the next iteration of the SPACE program are suggested by the results of this study. Most importantly, a change in the location of the field program should be considered. For studies of eastward propagating systems, the area of the Front Range east of South Park as well as the Palmer Lake Divide should receive maximum attention. This should include a reliable research radar (instead of using NWS Limon data) which will view the foothills "hot spots" continuously, as well as possible Doppler radars located to view one particular hot spot. Numerous surface stations should also be located in the eastern foothills, especially in regions which should have morning upslope winds advecting plains moisture into the foothills.

A rawinsonde station should be located in the foothills near the expected zone of transition between the deep heated boundary layer of the mountains and the suppressed PBL of the plains. Rawinsondes located to the north and south, giving a better 3D data set for use in initializing mesoscale numerical models, should be considered if resources permit. A detailed mesoscale data set emphasizing boundary layer flow in the Front Range area as well as certain east-forcing valleys would be of great value to air pollution studies of the Denver basin; hence, some new sources of funding could be uncovered.

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16. Abstracts

Two detailed, multi-sensor case studies of mesocale convective storms occurring in summer over the central and eastern Colorado Rockies are presented. These case studies use data taken during the 1977 South Park Area Cumulus Experiment (SPACE) from surface meteorological stations, rawinsondes and tethered balloons, conventional and Doppler radars, powered aircraft, and satellites. The case studies are compared with previous observations and theories relating to diurnal patterns of convective storm activity, especially those relating to thermal forcing of the boundary layer by the daily cycle of solar heating on elevated terrain.

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